Socio-economic, technological and environmental drivers of spatio-temporal changes in fishing pressure

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Abstract

As part of an ecosystem based approach to fisheries management (EBFM), the heterogeneity of biological communities, key ecological processes such as population connectivity and interaction webs, as well as heterogeneity of human uses must be understood. Although fishing effort distribution and marine habitat distribution and use are increasingly well understood, little research has quantified spatio-temporal changes in fishing effort or investigated drivers of these changes.

Here, a holistic approach was taken to investigate socio-economic, environmental and technological drivers of change in fishing effort distribution of the Northumberland pot-fishery (2004-2014) using Bayesian Belief Network (BBN) analyses. BBNs were populated using large-scale high resolution spatial and temporal fisheries monitoring data, quantitative and qualitative interviews with fishers and expert opinion. BBNs describing the relationships and influences of drivers on potting effort were produced for each season (winter, spring, summer and autumn) at two time periods: T1 (2004-2009) and T2 (2010-2014). The sensitivities of node *Fishing effort* to the influence of parent nodes were compared between seasons for T1 and T2. Temporal changes in Northumberland fishery were investigated by plotting mean seasonal change of BBN node values between T1 and T2.

The five variables which had the greatest influence on fishing effort distribution were: the distance from shore that fishermen were observed fishing; the proportion of days that fishermen chose to leave port; habitat type of fishing grounds; climatic conditions; and fishing vessel capability. Consistent changes in values and distributions of these variables were shown between T1 and T2. Large increases were observed in variables explaining the fleet's fishing capability, vessel capability and number of pots each vessel fished. Smaller but consistent increases were observed in the proportion of days that fishermen chose to leave port and engine sizes of fishing vessels.

A combination of changes in fleet composition and fishers' behaviour explains the observed increase in fishing effort between T1 and T2. Increasing vessel and engine sizes, combined with an increased uptake of improved fishing technology have resulted in a greater ability for vessels to fish a greater number of pots. In addition, this increase in vessel and fishing capability has resulted in fishers' increased ability

to fish in harsher weather conditions, as well as target specific areas or habitats quickly and opportunistically. Although larger, more capable fishing vessels have a larger maximum safely navigable distance from shore – few changes in the distance of fishing grounds were observed within the inshore fishery (<6NM from shore), suggesting pot-fishing distribution was also strongly governed by factors such as target abundance and catch and habitat type.

Non-technological factors also contributed to the observed increase in potting effort between T1 and T2. Declines in stocks of finfish and nephrops and the increasing operational costs of maintaining and participating in these fisheries may have resulted in many fishers solely fishing in the less regulated pot fishery targeting high value lobster on a full time basis. Increasing costs of pot-fishing in Northumberland coupled with stagnating crab and lobster landings prices may have resulted in increased fishing effort to maintain profitability.

1. Introduction

1.1. Background

Fishing provides an important socio-economic function in many parts of the world as a source of food and income (Kaiser 2014, Pauly et al 2002). Approaches to achieve sustainable management of fisheries have had mixed results but ecosystem-based fisheries management (EBFM) is considered best practice (Armstrong & Falk-Petersen 2008, Howarth et al 2011, Pikitch et al 2004, Salomidi et al 2012). EBFM requires understanding of the heterogeneity of biological communities, key ecological processes such as population connectivity and interaction webs, as well as the heterogeneity in exploitation practices (Crowder & Norse 2008). Knowledge of fisheries effort distribution and marine habitat usage (Kaiser 2014) is a prerequisite for spatial fisheries management, for example, changes in spatial distribution of fishing effort must be taken into account for the interpretation of catch per unit effort (CPUE) trends (Daw 2008, Jennings et al 2009, Walters 2003).

Previous research describing fishing effort distribution and differential use of marine habitats exist (Breen et al 2014, Lambert et al 2011, Nilsson & Ziegler 2007, Stelzenmüller et al 2008, Vanstaen & Breen 2014), the number of studies increasing with the development and use of vessel monitoring scheme (VMS) technologies (Diesing et al 2013, Jennings & Lee 2012, Lambert et al 2011, Piet & Hintzen 2012) and surveillance methods (Breen et al 2014, Des Clers et al 2008, Turner et al 2015). Fishing spatial patterns can vary over time (Kaiser et al 2002, Nilsson & Ziegler 2007), although little research has quantified spatio-temporal changes in fishing effort (Stelzenmüller et al 2008, Stephenson et al 2017) or investigated drivers of these (Stephenson et al 2017). Yet understanding such drivers is necessary for successful spatial management (Crowder & Norse 2008).

1.2. Drivers of fishing effort and distribution

Fishing effort and distribution are determined by fishers’ behaviour within the constraints of the fishery and its management system (Salas & Gaertner 2004). The majority of spatial fisher behaviour studies are for temperate commercial fisheries (Daw et al 2011), where appropriate data are routinely collected (see Branch et al (2006) for a review). Many of these data-rich economic modelling studies use a profit maximisation approach to study fisher behaviour (van Putten et al 2012), however, the underlying assumptions of this approach are debated as the heterogeneity of fisher behaviour is not always captured (Salas & Gaertner 2004) (see Table 1 for further information). A qualitative approach may be more appropriate in order to understand the complexity and context-specific behaviour of fishers (Daw et al 2011, Salas & Gaertner 2004). Several studies have used both quantitative and qualitative data to investigate drivers of fishing effort and distribution, concluding that socio-economic, ecological, technological and biological drivers can influence these (Andersen et al 2012, Béné & Tewfik 2001, Hilborn & Walters 1992, Salas & Gaertner 2004). However, the importance of individual drivers of fishing behaviour may differ between fisheries and study areas because of differing target species, technological availability and fishers' social and cultural norms (Table 1). In addition, these drivers often do not affect behaviour in isolation. Table 1 summarises some of the current understanding of drivers affecting fishing behaviour and possible interactions among these in temperate climates.

Table 1. Synthesis of the primary socio-economic, environmental, biological and technological drivers of fishing effort and distribution.

Field	Driver	Description	Interactions with other drivers
Socio-economic	Profit maximization	This assumes that fishers will select fishing locations which maximise their profit per unit effort (Abrahams & Healey 1990). Clearly this is an important consideration because fishing is primarily an economic activity (Chollett et al 2014, Daw 2008). The Ideal Free Distribution (IFD) has been used to investigate aggregated fleet behaviour (Abernethy et al 2007, Abrahams & Healey 1990, Fretwell & Lucas 1969, Swain & Wade 2003) and more recently using individual based discrete choice models (Holland 2008, Valcic 2009, Wilen 2004). The main costs of fishing include: cost of the vessel; travel time and distance (opportunity costs – the time spent travelling could be used to fish in areas closer to port); fuel costs; technological improvements; employment, and management fees (Abernethy et al 2010, Daw 2008, Turner et al 2012).	The most profitable areas will be determined by habitat type and quality and target species abundance (Pet-Soede et al 2001). Empirical evidence suggests that fishers do not distribute their effort perfectly according to profitability because they make decisions under uncertainty (Holland 2008), are constrained by resource space (see *fisher interactions*) and ability of fishers or their boats (see *vessel capability*), have incomplete knowledge of resource distribution (see *resources and habitats*)(Pet-Soede et al 2001) and can be restricted in their activities by fisheries *management* (Daw 2008*)*.
	Risk	The distance vessels are willing to travel is a consequence of economic risks (see *Profit maximisation*) and/or the level of physical risk. Generally, economic and physical risks increase with distance from shore (Daw 2008). The concept of “friction-of-distance” has been used to understand the inverse linear relationship of distance on location choice (Caddy & Carocci 1999). However, the relationship between risk and reward may not be linear, the perception of risk may have thresholds, e.g. at a certain distance vessels may not be able to return to port before nightfall (Daw 2008). Fishers with rewarding opportunities will be unlikely to travel far or explore new areas due to the high opportunity costs of travel time (Daw et al 2011). It has often been assumed that fishers are risk averse, however, this is debatable. Some experimental results suggest that fishers tend to favour consistency of catch over large but uncertain profits (Holland 2008). In other studies risk perception of fishers was found to be heterogonous, context specific and different between locations (Eggert & Lokina 2007, Eggert & Martinsson 2004, Strand 2004).	Physical risks may be increased due to adverse weather (see *Climatic conditions*) i.e. damage to vessel, damage to fishing gear and fisher injuries. Economic risks can be mitigated by fishers having knowledge of resources and habitats available (see *Resources and habitats*).
	Social-norms	Informal rules and social-norms can dictate fisher spatial behaviour (Daw et al 2011, Schlager & Ostrom 1992). For example, access to fishing grounds may be limited by customary tenure (Acheson & Brewer 2003, Turner et al 2012), ethnicity or caste systems (Alam et al 1996, Coulthard 2008).	Fishers may repeatedly target the same grounds because of ‘tradition’ and may not target the best available resources or habitats (Abernethy et al 2007). Informal rules can be formalised by managers, i.e. see *management*
	Fisher interaction	Fisher interactions can be positive (i.e. information sharing, observing other fishers and their catches), or negative (i.e. conflicts, gear theft, avoidance of	Fisher interactions may change over time, for example, fishing competitively and independently (no information sharing) when

		other fishers or fishing areas) (Acheson 1975, Gillis & Frank 2001). These interactions may determine choice of fishing location, e.g. knowledge of high catches passed on by a family member (Turner et al 2012) or through observation of boats at sea (Durrenberger & Palsson 1986), or avoidance of an area due to overcrowding or conflict (Acheson & Brewer 2003).	fishing is good, but cooperating and pooling catches during periods of the year when fishing is poor (Salas 2000). This may also change seasonally (see *climatic conditions*) with higher cooperation during months with poor weather (Salas 2000).
	Fisher personality	Fishing strategies or decision making may differ between individual fishers (Andersen et al 2012, Wilen 2004). Decision making is not always rational and logical pathways may be overlooked in favour of habitual behaviour (Salas & Gaertner 2004).	For management purposes, these individual strategies have been grouped into fisher 'typologies', i.e. fishers that have similar vessel capability and gear types (see *vessel capability* and *fishing technology*), target similar species and make similar decisions (Boonstra & Hentati-Sundberg 2014). However, oversimplifying fishers' tactics into categories does not always capture the adaptive and dynamic nature of fishers' behaviour (Salas & Gaertner 2004).
	Management	Spatial management can alter where fishers fish, for example, through fisheries exclusion, zonal management (Cinner 2007) or increasing costs (i.e. purchasing licences, quota).	Fisheries management may alter spatial fishing patterns, for example increased concentration of fishers in remaining fishable areas, increased competition for resources (see *Resources and habitats*) (Guenther et al 2015) or exit of the fishery due to increased operational costs (see *Profit maximization* and *Risk*).
Environmental	Climatic conditions	Climatic conditions are important drivers of fishing behaviour (Turner *et al*., 2012), affecting choice of fishing location (Daw 2008) and fishing activity (Chollett et al 2014) – adverse weather conditions can stop fishers from fishing or restrict them to sheltered areas, for example, sheltered inshore reefs (Teh et al 2007). Adverse weather also increases fishing risks (see *Risk*), for example damage to fishing gear (Lewis et al 2009).	The degree to which climatic conditions will affect fishing location will be dependent on fishers' technological resources (see *vessel capability*) (Daw et al 2011, Wilen et al 2002, Williams et al 2008), the degree of risk fishers are willing to operate in (see *risk*) (Dowling et al 2015, Smith & Wilen 2005) and is variable by location and fishery (Chollett et al 2014). The maximum safely navigable distance will limit the size of the available resource space (Daw et al 2011) with many fisheries exhibiting seasonal patterns; smaller fishable areas in winter compared to summer (Teh et al 2007), but at the simplest level, these can be expanded by fishers operating larger vessels. Increasing ratio of fishers:available resource space may increase competition among fishers (see *competition*) (Acheson & Brewer 2003).
Biological	Resources and habitats	Spatial distribution of resources and habitats will affect fisheries distributions (Pet-Soede et al 2001) because fishers will actively seek and target certain habitats or areas with high catches (within their ability to perceive these) (Nilsson & Ziegler 2007, Stelzenmüller et al 2008). These will differ between fisheries, for example, smooth ground may be targeted for trawling (Rijnsdorp et al 2001), reefs may be targeted for scallop dredging (Lambert et al 2011), and target species may aggregate seasonally (Swain & Wade 2003).	Fishers may be better able to target resources and habitats through fishing experience i.e. accumulating local knowledge of the area (Turner et al 2012), or through the use of technology such as echo-sounder and GPS (Daw 2008) or by monitoring trends in catch (Eales & Wilen 1986) (see *vessel capability*). They may also maximise their CPUE by purchasing more efficient fishing gears (see *Fishing technology*)

Technological	Vessel capability	Vessel capability includes vessel size, engine size, gear type (Gaertner et al 1999, Tzanatos et al 2006). Vessels of different fishing capabilities may target different fishing grounds (Breen et al 2014, Williams et al 2008), for example larger vessels may target grounds further offshore if these are perceived as having higher catch (see *resources and habitats*) and with differing effort (le Pape and Vigneau, 2001).	Investment in vessel capability may change the profit per unit effort (see *profit maximisation*) and alter economic risks (see *risks*). E.g. purchasing a larger vessel may allow exploration in areas further from port but in turn, catches must be high in order to pay for the higher costs of the vessel, fuel and travel time.
	Fishing technology	Availability of technology such as echo-sounder and GPS (Daw 2008), methods for monitoring trends in catch (Eales & Wilen 1986) and more efficient fishing gears can determine both choice of fishing location and effort levels.	Costs to fishermen may increase due to purchasing new technologies or modifying fishing gears.

Interdisciplinary studies have examined the influence of multiple drivers on fisher behaviour (Andersen & Christensen 2005, Andersen et al 2012, Christensen & Raakjær 2006, Marchal et al 2009, Wilen 2004) but we are aware of no studies that aim to understand how drivers of fisher behaviour change over time and the subsequent impacts on fishing effort and distribution. The large multidisciplinary data sets required and the different scales and formats in which these data are collected make modelling multiple drivers of fisher behaviour challenging (Andersen et al 2012, Daw 2008, Wilen 2004).

BBNs are a flexible modelling tool that can combine causal expert knowledge and empirical evidence-based data (Naranjo-Madrigal et al 2015) to challenge assumptions and investigate scenarios. BBNs consist of a directed acyclical graph (DAG) (Naranjo-Madrigal et al 2015, Stelzenmüller et al 2011) which is a graphical representation of the causal relationships which is then supported by the available data and knowledge. The graphical nature of these models conveys complex information in an intuitive manner that is easily interpreted by non-technical managers (Choy et al 2009). Thus these modelling tools can be used to effectively bridge the gap between scientific investigation and management implementation (Choy et al 2009, Fulton et al 2007). BBNs have successfully been used for a range of natural resource management problems (Landuyt et al 2013, Marcot et al 2001, Marcot et al 2006, Nyberg et al 2006, Rieman et al 2001) and they are increasingly used to investigate spatial processes, e.g. marine spatial planning (Naranjo-Madrigal et al 2015, Stelzenmüller et al 2010, Stelzenmüller et al 2011), fisheries habitat suitability (Fulton et al 2007) and mapping ecosystem services trade-offs (Gonzalez-Redin et al 2016).

This study investigates socio-economic, environmental and technological drivers of change in inshore pot-fishing effort distribution in Northumberland. Declines in stocks of finfish may have resulted in increasing pot-fishing in the UK (Acheson & Brewer 2003, Molfese et al 2014, Stephenson 2016, Turner et al 2012) yet little is known about spatio-temporal patterns in potting effort and associated drivers (Stephenson et al 2017). The lobster fishery in Maine has evolved over time due to fishers' responses to market forces (Steneck et al 2011), informal rules amongst fishers (Acheson & Brewer 2003, Brewer 2010), lobster population responses to changes in oceanographic conditions (Holland 2011, Incze et al 2006, Steneck & Wilson 2001, Zhang et al 2011) and to harvesting practices within the fishery (Acheson 1988, Acheson & Brewer 2003, Brewer 2010). Fishers in the UK are likely to adapt and evolve their practices in response to similar ecological and behavioural drivers (Turner *et al.,* 2015) but to improve decision making, context specific drivers must be understood.

The present study site in Northumberland is rare for the large-scale high-resolution spatial and temporal multidisciplinary data sets (see Methods). There has been significant change in fishing effort and spatial distribution between 2004 and 2014 (Stephenson et al 2017). Here the unique combination of these temporal fisheries effort distribution data with fishers' local ecological knowledge in a BBN analysis allowed identification of the relative importance of different drivers. We contextualise the socio-ecological results of the BBN using fisher interview data, and highlight often-overlooked social and technological drivers of fishing effort distribution.

2. Methods

2.1. Description of case study area

The waters of the Northumberland Inshore Fisheries & Conservation Authority (NIFCA) extend 6 nautical miles (NM) offshore, from the River Tyne in the South to the Scottish border in the North (Fig 1). The fishery is mixed (Garside et al 2003), largely operating close to shore (<6NM) and primarily composed of <10m fishing vessels (n=70±9% between 2003 and 2014; Stephenson et al 2017). The majority of Northumberland fishers target crustaceans: European lobster (*Homarus gammarus*), edible crab (*Cancer pagurus*) and to a lesser extent, velvet crab (*Necora puber*), using baited pots (or traps). Only the pot-fishery was investigated in this study.

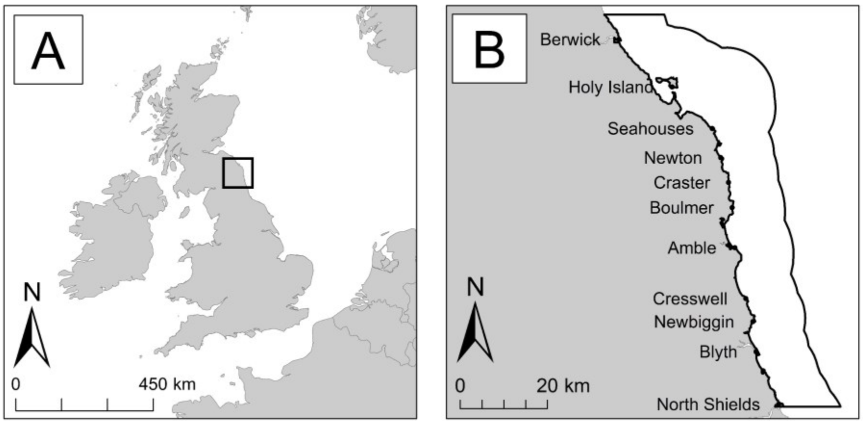


Fig 1. Location of Northumberland inshore waters (NIFCA district) in Great Britain.

Pot-fishing effort and distribution vary seasonally in Northumberland - primarily due to changes in weather as well as coinciding seasonal biological cycles and movements of target species (Daw et al 2011, Skerritt et al 2015, Turner et al 2012) – and follow a cyclical pattern with highest potting effort in summer steadily declining from autumn to winter and increasing again in spring (Garside et al., 2003). In order to reduce the variability in fisher behaviour, effort and distribution associated with known seasonal fishing cycles (Marcot et al 2006), BBNs were produced for each season: winter (Jan-Mar), spring (Apr-Jun), summer (Jul-Sept) and autumn (Oct-Dec) (Fig 4) (details below).

Pot-fishing effort in the study area increased substantially between 2004 and 2013 (233 642–354 193 pots year^{-1}) and fishing effort distribution differed between individual years, decreasing over large areas between 2004 and 2009, and increasing especially inshore between 2010 and 2014 {Stephenson, 2017 #22} (Fig 2). In order to investigate differences in drivers of observed changes in fishing effort and distribution over time, BBN analysis for each season were compared between two time periods: 2004-2009 (termed T1) and 2010-2014 (termed T2).

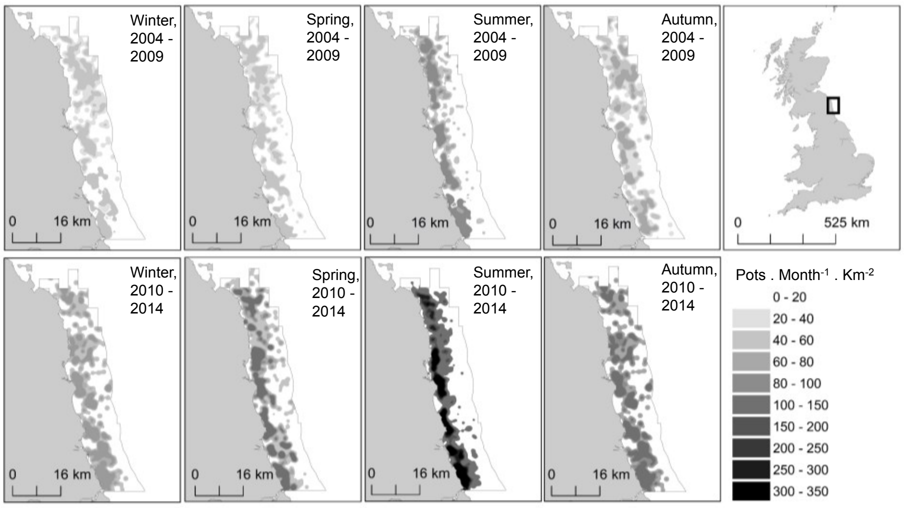


Fig 2. Potting effort distribution (pots.month^{-1}.km^{-2}) in NIFCA areas with high – moderate confidence (grey outline). Potting effort distribution modelling using data and following methods from Stephenson *et al.*, 2017.

2.2. *Data collection*

The BBNs were populated using several methods and data sets (fisheries landings and effort, fishing vessel sightings at sea, Met office inshore sea state, single beam echosounder, quantitative interviews with fishers and semi-structured questionnaires from key informants) described in the following sections.

2.2.1. *Fisheries effort and vessel sightings data*

Monthly Northumberland shellfish landings data for 2001-2014 provided by the NIFCA included vessel name, length, engine size, number of pots worked per month, home port, landing port and mass of landed target species. Fishing vessel sightings including vessel name, registration, home port, geographic position and observed activity were also recorded during routine NIFCA patrols between 2004 and 2014. Sightings in 2004-2014 of vessels which were observed hauling or deploying pots targeting crab and lobster mapped as point data, were standardized by NIFCA patrol effort, and transformed to a continuous surface using a non-parametric quadratic kernel density estimation (KDE) method in Esri GIS ArcMap 10.2 (Silverman 1986). These data were then combined with landings data to estimate and map fishing activity between 2004 and 2014 following Turner et al (2015) and Stephenson et al (2017).

2.2.2. *Habitat Type*

Substrate hardness data was obtained through the NIFCA patrol vessel's Olex software, which calculates a relative hardness based on the ratio of sent and received acoustic energy measured from the vessel's single beam echo-sounder. Olex ranges from a scale of 1 (low reflection, indicating soft ground) to 100 (high reflection indicating hard rocky ground) (Skerritt et al 2015). Although Olex does not assess the bottom roughness and therefore does not allow discrimination of fine scale habitats, it provides broad substrate classification (Elvenes et al 2014, Skerritt et al 2015) at the scale most likely used by fishermen (Stephenson 2016) (Fig 3).

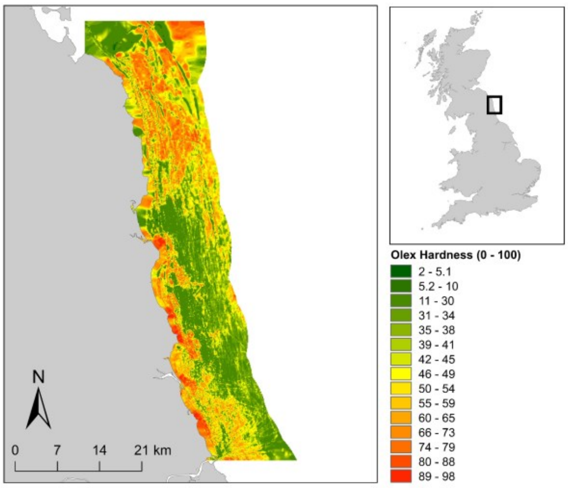


Fig 3. Acoustic Olex hardness data (1 – 100) for Northumberland.

2.2.3. *Weather data*

Twenty random days per month of inshore sea state data were obtained for the area from Berwick upon Tweed to Whitby from 2006-2014 (Met office, area 3). This included information on sea state, wind speed and direction.

2.2.4. *Fisher interviews*

Quantitative interviews of fishers (*n*=25, ca. 60% of active fleet, June 2015) and semi-structured interviews with key informants (*n*=6, ca. 10% of active fleet, May 2016) were conducted at four ports (Seahouses, Boulmer, Amble and Blyth, Fig 1) in Northumberland. Key informants were experienced fishermen who were leaders of fisher associations and/or participated in regional management stakeholder meetings. After initial contact with two key informants, subsequent interviewees were contacted by snowballing (Bunce et al 2000, Turner et al 2015).

2.3. *Questionnaire*

The questionnaire aimed to investigate drivers behind decisions to fish and followed approaches from previous studies (Andersen & Christensen 2005, Daw et al 2011, Des Clers et al 2008, Holland & Sutinen 1999, Turner et al 2015). This covered areas such as vessel capability, weather and seasonal influence on decision-making, target catch and perceptions of habitat (questionnaire in supplementary materials). Fishers' responses to the quantitative and semi-structured questionnaires were summarised and drivers of fishing effort and distribution were categorized into themes: environmental, fisheries management, economic, social and technological (supplementary materials, Table A1). Quantification of expert knowledge used to inform the BN model followed best practice of Choy et al (2009).

2.4. *Bayesian Belief Network development*

BBNs were created using Netica software (version 5.18, Norsys Software Corporation) to explain fishing effort in Northumberland. Briefly, the model structure was depicted in a directed acyclical graph (DAG) (Naranjo-Madrigal et al 2015, Stelzenmüller et al 2011), where causal relationships (links) between the variables (nodes) are shown as arrows (Fig 4). Data and expert knowledge were used to populate the conditional probability tables (CPT) that define the probability distribution of the nodes conditioned upon the values of the parents nodes (Marcot et al 2001). Nodes that do not have parents nodes simply display prior distribution (Pearl 2003).

The BBN was developed following a logical framework by Marcot et al (2006). Several iterations of BBN structure, variable definitions and CPTs were produced through literature review (Table 1) and direct elicitation of fisheries and BBN experts (Low Choy et al 2009). Final structure and variable definitions were produced through indirect expert elicitation of key informants (Choy et al 2009). CPTs were populated through a combination of data (quantitative and semi-structured interviews, fisheries landings, GIS layers and inshore sea state data, Table 2), and expert opinion. The final BBN structure and variables used to investigate Northumberland fishing effort is shown in Fig 4 and Table 2, respectively.

Continuous variables (Table 2) were discretised in order to maximise the interdependence of variables whilst ensuring minimal information was lost (Naranjo-Madrigal et al 2015, Nielsen & Jensen 2009). The supervised discretisation method was used to transform continuous data for BN analysis (Alameddine et al 2011, Liu et al 2002). For example, the variable *Engine size* was populated using NIFCA monthly landings data, where the recorded engine size in horse power (hp) for each registered vessel per month was categorised based on the mean engine size that fishers considered small, moderate or large during the key informant questionnaires. CPTs were calculated for each variable using the expectation-maximisation algorithm in Netica (Korb & Nicholson 2010) and each node was checked for consistency with estimated probabilities from expert opinion (Marcot et al 2006).

Performance of the BBN was evaluated using sensitivity analysis; the sensitivity of node *Fishing effort* to the influence of parents nodes was calculated using a variance reduction method (Marcot et al 2006). Variance reduction scores were compared between seasons for T1 and T2. Temporal changes in Northumberland fishery were investigated by plotting mean seasonal change of BBN node values between T1 and T2 (Grainger and Stuart, in publication).

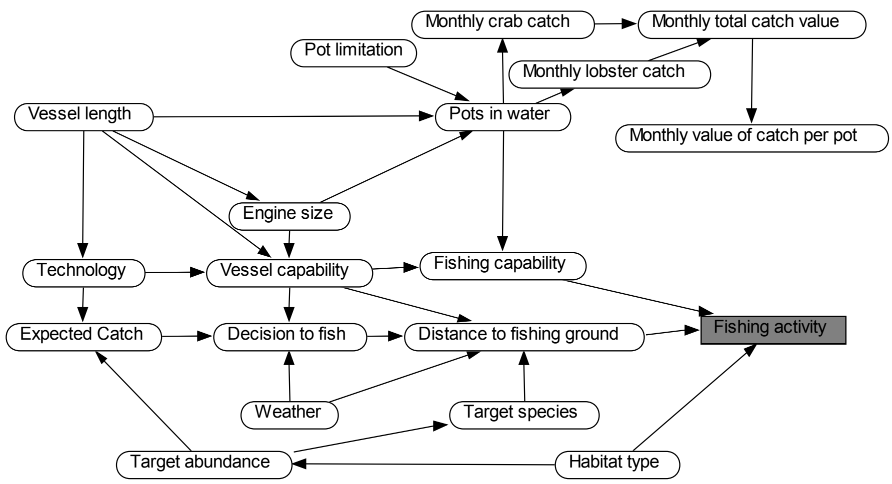


Fig 4. Conceptual BBN model showing variables that affect pot-fishing activity in Northumberland.

Table 2. Description of social and technological, management, economic, biological and environmental nodes used to populate BBN models of Northumberland potting activity.

Node name	Definition, methods & units	Type	States	Parent nodes	Relationship	Assumptions
Fishing activity	Raster layer (resolution: 500 x 500m) of predicted potting activity distribution in areas of moderate - high confidence in the NIFCA district (Fig 2, pots.km^{-2} .month^{-1}). Modelled from a combination of vessel sightings data (adjusted for patrol effort) and landings data for areas of moderate and high confidence in the NIFCA fishing district (Stephenson 2016, Turner et al 2015). Raster pixels were extracted as a CSV file and frequency of fishing effort values used in the BBN.	Terminal node	0 – 20 20 – 40 40 – 60 60 – 80 80 – 100 100 – 150 150 – 200 200 – 250 250 – 300 300 – 350	• Pot limitation	• Pot limitation imposes an 800 pot limit for each vessel within the NIFCA district (max 800 pots.vessel $^{-1}$.month $^{-1}$).	Modelled potting activity distribution is accurate (Breen et al 2014, Turner et al 2015)
				• Habitat type	• Fishers show preference for certain habitats (Nilsson & Ziegler 2007, Stelzenmüller et al 2008, Stephenson 2016).	
				• Target species	• Fishers' effort distribution is influenced by changes in distribution of target species abundance (Acheson 1975, Salas & Gaertner 2004)	
				• Distance to fishing ground	• Distribution of fishers is affected by their decision to target fishing grounds at various distances from port (Daw 2008, Gaertner et al 1999).	Territoriality of pot fishers in Northumberland (Turner et al 2012) limits fishers' north - south movements.
				• Potting capability	• Vessels of different fishing capabilities will target different fishing grounds (Breen et al 2014) and with differing effort (le Pape & Vigneau 2001).	
Potting capability	The number of active potting vessels (i.e. vessels that are landing catch) in each capability category. This is a measure of how many pots a single vessel can fish which is a combination of the physical characteristics of the vessel and the number of pots the skipper owns and is fishing per season. Classification based on expert elicitation, and NIFCA landings data.	Technological	High Moderate Low	• Vessel capability	• Vessels of different capabilities will have different potting capabilities (i.e. large boats with large engines will have the ability the fish a greater number of pots per day, whereas smaller boats with small engines will only be able to fish a small number of pots).	
				• Pots in the water	• The number of pots owned and fished by individual vessels provides an indication of fishing strategy (i.e. large boats may only have small number of pots as they focus on other target species, whereas small boats may have large number of pots which are only deployed in summer when weather allows these vessels to fish almost continuously)	
Pots in water	The number of pots at sea for each vessel. Obtained from the NIFCA effort data. The number of pots each vessel owns will be	Technological	0 – 100 100 – 300	• Vessel length	• The number of pots a vessel is able to fish in a day will be dependant on the vessel length	

	limited by vessel length and engine size, both of which, limit the number of pots that can be fished in a day, as well as the number of pots that can be moved in a day if bad weather forces pots to be moved offshore to deeper water (see weather node).		300 – 500 500 – 800	 • Engine size • Pot limitation	(and installed technology, which is also limited by vessel length) • Number of pots that can be fished per day will be limited by how quickly a vessel is able to travel between sites, this is limited by engine size. • The number of pots that a fisher can fish in the NIFCA district was capped to 800 in 2009.	
Pot limitation	NIFCA byelaw 4 (para 5) limiting the number of pots fished within the NIFCA district (up to 6NM from coast) to 800 per vessel, implemented in 2009 (NIFCA 2014).	Management	Yes No	• None		
Monthly crab catch	Monthly crab landings (kg) for each active fishing vessel in Northumberland. Obtained from the NIFCA effort data.	Economic	0 – 500 500 – 1000 1000 – 1500 1500 – 2000 2000 - 12000	• Pots in water	• Crab catch of each vessel will be limited by the number of pots that vessels fish with each month.	
Monthly lobster catch	Monthly lobster landings (kg) for each active fishing vessel in Northumberland. Obtained from the NIFCA effort data.	Economic	0 – 500 500 – 1000 1000 – 1500 1500 – 2000 2000 - 6600	• Pots in water	• Lobster catch of each vessel will be limited by the number of pots that vessels fish with each month.	
Monthly total value of catch	Monthly crab and lobster values (£.kg^{-1}) were obtained from NIFCA quarterly reports. Monthly total value of catch was calculated by multiplying monthly crab and lobster landings (kg) for each fishing vessel with catch values which were adjusted for annual inflation so as to reflect 2014 values.	Economic	0 – 1500 1500 – 4000 4000 – 7500 7500 – 15000 15000 - 30000	• Monthly crab catch • Monthly lobster catch		
Monthly value of catch per pot	Total monthly value of catch was divided by the number of pots each vessel fished in a month to provide a measure of fishing efficiency (£.pot^{-1}).	Economic	0 – 10 10 – 20 20 – 30 30 – 50 50 - 165	• Monthly total value of catch • Pots in water		
Habitat type	Raster layer of Olex hardness (resolution: 500x500m). Modelled from interpolation of the NIFCA patrol vessel's single-beam echo sounder data (Elvenes et al 2014, Skerritt et al 2015) Classification of ground type: Hard (Olex value: 46-98), Mixed (Olex value: 31-46) and Soft (Olex value: 2-30). Shellfish species use habitats differently; their distributions, movements and abundances are influenced by habitat type, quality	Environmental	Hard Mixed Soft	None		Modelled habitat data is accurate (Elvenes et al 2014, Skerritt et al 2015).

	and location (Galparsoro et al 2009, Geraldi et al 2009, Skerritt et al 2015). Lobster (*Homarus gammarus*) and velvet crab (*Necora puber*) are found predominantly on shallow rocky ground although lobster can also be found at 60m or deeper (Galparsoro et al 2009, Wilson 2008). The edible crab (*Cancer pagurus*) is found in all habitat types but evidence suggests preferences for coarse sediment and offshore muddy sand (Neal & Wilson 2008). Inshore fishermen in Northumberland target specific habitats in order to maximise their target catch. Raster pixels were saved as a CSV file and frequency of substrate hardness used in the BBN.					
Target species	The proportion of target species (crab, lobster or both) that fishermen are targeting. This varies greatly between seasons, with heavy targeting of lobster in summer months and a greater focus on crab in winter months. Data obtained through expert elicitation (questionnaire) and monthly NIFCA landings data.	Social	Crab Lobster Both	• Target abundance • Habitat type	• Perceived abundance determines which species fishers' target (Christensen & Raakjær 2006). • Habitat type determines abundances of target species (Geraldi et al 2009), thus fishers target specific habitats (Stephenson 2016)	
Target abundance	The perceived abundance of crab and lobster. Data from expert elicitation (i.e. seasonal abundance and behaviour of target species) and review of the literature. Crab and Lobster are thought to be most abundant in the NIFCA district in summer when these are active and feeding (more catchable in baited traps) on shallow inshore reefs. In winter, crab and lobster are thought to move to deeper water further offshore where temperature and turbidity remain more constant than in shallow water.	Environmental	Crab high Crab low Lobster high Lobster low	• Habitat type	• Habitat type will determine the abundance of target species (Geraldi et al 2009): lobster predominately found on hard ground (Galparsoro et al 2009) and brown crab is found in all habitat types but may have a preference for soft ground (Neal & Wilson 2008). Subtleties for Northumberland obtained in expert elicitation.	Lack of fisheries independent data; fishers' perception of abundance may reflect catchability rather than actual abundance of target species in habitats (Addison 1995, Skerritt et al 2015).
Distance to fishing ground	The number of fishers that choose to fish (or not) on grounds at various distances (NM) from the coastline. In Northumberland, there is a positive relationship between distance from shore and water depth (i.e. as distance from shore increases, so will water depth). Distance from shore was measured for each fishing vessel sighted during routine enforcement patrols using ARC GIS. Supervised categorization using results from key information questionnaire.	Social	0 0 – 1 1 – 3 3 – 6	• Target species • Weather • Decision to fish • Vessel capability	• Distance to fishing ground may vary if targeting lobster or crab (Turner et al 2012). Fishermen "follow the stock", fishing close to shore in summer and moving further offshore to deeper water during the winter. • Weather affects how far from shore fishers choose to fish (damage to gear, safety, time) (Turner et al 2012). • If fishers decide not to fish then distance was classified as 0. • Vessel capability will determine how far fishers can / are willing to go from shore (Gaertner et al 1999, Tzanatos et al 2006).	

Weather	Number of days which have good (probable wave height <1m; mean wind speed <7 Knots) moderate (probable wave height <2m; mean wind speed <12 Knots) and bad weather (probable wave height >3m; mean wind speed >15 Knots). Seasonal averages calculated from daily area 3 (Berwick upon Tweed to Whitby) *inshore waters and strong winds forecasts* from 2006-2014. Data obtained from the Met Office. Categorisation of data defined during expert elicitation. Weather condition is an important driver of fishing behaviour (Turner *et al.,* 2012), adverse weather can cause damage to gear (especially in shallow water where pot movement occurs (Lewis et al 2009)) and reduced catches (target species are "holed" up, not feeding and as such are not catchable). Offshore, deeper water will be less affected by adverse weather than shallow inshore water, the depth at which this is true is related to the intensity of adverse weather. The ability to fish in adverse weather will be dependent on vessel capability. During good weather fishermen with vessels of all capabilities will have the opportunity to fish in areas which they feel will have the best catches. In moderate and bad weather, fishermen will be restricted by the capability of their vessels and will fish further offshore to reduce the negative impact of increased wave and wind action on their fishing gear and catches.	Environmental	Good Moderate Bad	None	
Decision to fish	The proportion of days fishermen hauled pots in each season. Data collected from NIFCA landings data.	Social	Yes No	• Weather • Vessel capability • Expected catch	• Bad weather may result in fishermen staying at port (Turner et al 2012) • Vessels with high capability may still choose to fish even in bad weather (ability to operate in larger swell and stronger winds). • Expected catch affects the decision to fish, i.e. fishers may not pot if there is low expected catch (Abernethy et al 2007, Abernethy et al 2010)
Vessel capability	The number of active potting vessels (i.e. vessels that are landing catch) in each capability category. Classification based on expert elicitation, and NIFCA landings data. Seasonally, this varies considerably with fewer active vessels of low capability in winter and a higher number of vessels of all capabilities in summer.	Technological	High Moderate Low	• Vessel length • Engine size • Technology	• Longer vessels may be able to fish more pots (deck space) and withstand worse weather conditions. • Engine size determines how fast the vessel can travel (more pots fished and ability to travel in worse weather conditions). • Vessel ability to maximise catch may be increased with increased technology (Gaertner et al 1999, Salas & Gaertner 2004)

Engine size	The number of active potting vessels with small, moderate and large engine horse power (HP) obtained by cross-referencing active vessel in Northumberland (NIFCA landings data) with European Union Fleet Register (http://ec.europa.eu/fisheries). Small (<100 HP), Moderate (100-200 HP) and Large (>200 HP). Definition of categories through expert elicitation.	Technological	Small Moderate Large	• Vessel length	• Vessels of different lengths will be able to accommodate different ranges of engine size. Vessel length-Engine size relationship was investigated for Northumberland using NIFCA landings data.	
Vessel Length	The number of active potting vessels in length overall (LOA) categories (4-6; 6-8; 8-10; 10-12 m) from NIFCA landings data.	Technological	4 – 6 6 – 8 8 – 10 10 – 12	None		
Technology	The proportion of vessels with both, either or no GPS or SBES. Estimated from expert elicitation. High (both GPS and SBES), moderate (Either GPS or SBES) and low (neither GPS nor SBES).	Technological	High Moderate Low	• GPS • SBES	• Availability of GPS and or SBES increases technology on-board fishing vessels.	
GPS	The proportion of vessels with GPS. Estimated from expert elicitation. Having GPS on board reduces reliance on landmarks, makes travelling to fishing grounds more time efficient and reduces the need to have long logbooks with description of areas fished, thus increasing fishing efficiency. The proportion of vessels which have GPS equipped has vastly increased between 2004 and 2014 due to increased affordability, with an estimated 99% of vessels equipped with GPS in 2014.	Technological	Yes No	None		
Single beam echo-sounder (SBES)	The proportion of vessels with SBES equipped. Estimated from expert elicitation. SBES allows fishermen to estimate ground type more efficiently than based on historical knowledge (i.e. determination of ground type based on catch). The proportion of vessels which have SBES equipped has also vastly increased between 2004 and 2014 due to increased affordability, with an estimated 90% of vessels equipped with SBES in 2014.	Technological	Yes No	None		
Expected catch	The proportion of fishers expecting high, moderate and low catches. Theoretical value informed from expert elicitation.	Socio – economic	High Moderate Low	• Target Abundance • Short term success • Historic knowledge	• Perceived abundance of target species will determine fishers expected catch (Rijnsdorp et al 2011). • If recent fishing grounds have had high catch the expectation may be that subsequent trips are also likely to have high catch up to a point (Rijnsdorp et al 2011, Turner et al 2012) • Knowledge gained over time may allow fishers to expect higher catches (i.e. more experience on when and where to fish,	Assumption that historic knowledge is still important: Expert elicitation revealed this was the case in Northumberland although with the wider and more affordable availability of technology this may be less important than in the past (Hilborn 1985, Salas & Gaertner 2004, Turner et al 2012)

				• Technology	resulting in higher catches)(Gaertner et al 1999). • Better technology means more accurate and quicker location of productive fishing grounds, therefore increasing the expected catch (Hilborn 1985).	
Historic knowledge	Proportion of fishers in each year category. The number of years (y) fishers have been potting in the NIFCA district was used as a proxy for historical knowledge. Data collected from previous social surveys (Turner *et al*., 2012; Newcastle University MSc projects)	Social	1 – 3 3 – 10 10 – 25 25 +	None		Assumption that the number of years in the potting fishery are an appropriate proxy for historical knowledge / experience. This doesn't take into account whether fishermen: are from 'fishing families', have gained fishing knowledge from using other gear types (i.e. netting, trawling) or how skilled individuals are at potting.
Short term success	The proportion of times fishers leave their pots on the same fishing grounds. Estimated through expert elicitation. Fishermen that regularly have high short term success are likely, overall, to be successful (Turner et al 2012). In order to have high short term success, fishermen must anticipate the combination of weather, target abundance and habitat in order to fish productive areas before other fishermen arrive (i.e. 'marking' an area) (Guenther et al 2015).	Social	Yes No	• Historic knowledge	• The location of a good fishing ground (i.e. high short term success) is influenced by experience (historical knowledge)	Assumption that technology does not affect short term success. Determined by expert elicitation.

3. Results

3.1. Seasonal changes in variables affecting fishing effort in Northumberland

The complete BBN models describing the relationships and influences of drivers on potting effort for all seasons and years are provided in the supplementary materials (Fig 7, Fig 8, Fig 9, Fig 10, Fig 11, Fig 12, Fig 13 and Fig 14). Seasonal differences were observed for variables *distance to fishing ground, weather, decision to fish, target abundance, monthly crab catch, monthly lobster catch, monthly total value of catch* and *monthly value of catch per pot*; values of other variables varied little between seasons (Table 3). Broadly, where distributions and values differed between seasons, values for summer and winter were the most dissimilar with spring and autumn having intermediate values and distributions (Table 3). Patterns of seasonal change were similar between periods T1 and T2.

Table 3. Summary of seasonal changes of variables affecting fishing effort in Northumberland in order of magnitude of changes.

Node	Summary of change
Distance to fishing ground	• Winter and autumn had similar distributions: high instances of fishers staying at port, little fishing inshore and higher fishing offshore. • Summer and spring had similar distributions: low instances of fishers staying at port, higher fishing inshore and less fishing offshore.
Weather	• Weather patterns varied seasonally with higher frequency of bad weather in winter and higher frequency of good weather in summer.
Decision to fish	• The proportion of days fishermen hauled pots was high summer and spring and was lower in winter and autumn
Target abundance	• Perceived abundance of lobster was highest in summer and autumn and lowest in winter and spring • Conversely, perceived abundance of crab was highest in winter and spring and lowest in summer and autumn.
Monthly crab catch	• Crab landings varied seasonally with high landings in winter and spring and lower landings in summer and autumn.
Monthly lobster catch	• Lobster landings varied between seasons with high landings summer and autumn and lower landings in winter and spring.
Monthly total value of catch	• Total value of catch varied between seasons with the highest values of landings recorded in summer and autumn and the lowest recorded in winter and spring
Monthly value of catch per pot	• Value of catch per pot followed a similar pattern to that seen in *monthly total value of catch*.
Target species	• The proportion of species targeted by fishers followed patterns of perceived *target abundance*
Vessel length	• Vessel length of the active fleet varied slightly between seasons. • Higher proportion of smaller boats (4-8m) active in summer compared to winter which had higher proportion of larger boats (8-12m).

Vessel capability	• Varied slightly. Similar proportion of high capability vessels across all seasons but higher proportion of fleet with low capability in summer and higher proportion of moderate capability in winter.
Expected catch	• Expected catch varied slightly between seasons • There was higher expected catch in summer compared to winter.
Technology	• Level of technology on board active vessels varied slightly between seasons • Higher number of vessels categorised as having high technology equipped in winter compared to summer.
Engine size	• Varied very little seasonally
Fishing capability	• Varied very little seasonally
Pots in water	• Varied very little seasonally
Pot limitation	• Did not vary between seasons
Habitat type	• Did not vary between seasons

3.2. Sensitivity analysis

Sensitivity assessment of BNN models determined the degree and rank order of the influence of parent nodes on the outcome of *fishing activity* (Table 4). Variance reduction was lowest in models for winter and highest in models for summer (Table 4). Overall, variance reduction was highest for variables across all models at T2 compared to T1 (Table 4). Five variables (*distance to fishing ground, decisions to fish, habitat type, weather* and *vessel capability*) consistently had the most influence on node fishing activity across the majority of seasons in T1 and T2, although the order of importance of these varied (Table 4). The variables *fishing capability* and *pots in the water* had a much greater influence on fishing activity in models for winter and summer in T2 than in T1 (Table 4). All other variables had much lower influence on end node fishing activity (Table 4).

Table 4. Results of sensitivity analysis for variables affecting fishing activity in Northumberland, seasonally and for T1 and T2. Values are calculations of variance reduction where high values indicate a high degree of influence on the node *Fishing activity*. Filled cells represent the five variables which had the most influence on node *fishing activity*, with darker colours indicating greater influence. Nodes which did not affect node *fishing activity* were excluded from the table.

	Variance reduction							
Node	Winter T1	Winter T2	Spring T1	Spring T2	Summer T1	Summer T2	Autumn T1	Autumn T2
Distance to fishing ground	34.000	301.000	52.440	440.800	840.300	4281.000	25.340	770.700
Decision to fish	6.384	1.937	5.198	63.860	520.800	2914.000	5.042	74.160
Habitat type	6.238	0.399	6.469	28.210	33.710	109.900	11.010	53.180
Weather	2.535	0.664	1.226	12.280	246.200	1650.000	1.849	21.800

Vessel capability	0.937	5.974	2.056	12.370	38.860	310.400	1.329	11.510
Vessel length	0.379	0.196	0.888	1.822	21.030	214.500	0.580	4.220
Fishing capability	0.373	2.891	0.149	6.051	28.880	406.700	1.008	8.123
Engine size	0.299	0.285	0.149	0.672	14.910	126.100	0.429	1.213
Pots in water	0.297	2.319	0.138	5.234	21.130	346.100	1.130	6.397
Technology	0.191	0.106	1.097	3.758	10.910	52.870	0.488	3.468
Target abundance	0.073	0.245	0.112	1.136	11.320	21.030	0.027	3.300
Target species	0.025	1.641	0.650	5.919	17.710	19.890	0.018	0.368
Expected Catch	0.022	0.015	0.044	0.268	2.026	9.477	0.044	0.651

3.3. Temporal changes in variables affecting fishing effort in Northumberland

Changes in CPT values of variables which differed between T1 and T2 are shown in Fig 5. Changes were consistent between seasons in T1 and T2, as highlighted by the narrow interquartile range and the clear distinctions between many of the categories (Fig 5). Consistent with other analysis (Fig 2, Stephenson *et al*., 2017) end node *fishing effort* differed between T1 and T2 (Fig 5). *Fishing capability, vessel capability* and *pots in the water*, all showed positive changes in their higher categories: increase in proportion of high fishing and vessel capabilities and increase in the proportion of vessels that fish with a high number of pots (500-800 pots) (Fig 5). In turn, between T1 and T2, *monthly crab catch* and *monthly lobster catch* increased, as did the *total catch value*. However, *value of catch per pot* changed very little between T1 and T2. Smaller but consistent changes were found for variables *decision to fish* and *engine size*: fishers were more likely to undertake fishing activities, and fishing vessels were equipped with larger engines in T2 compared to T1.

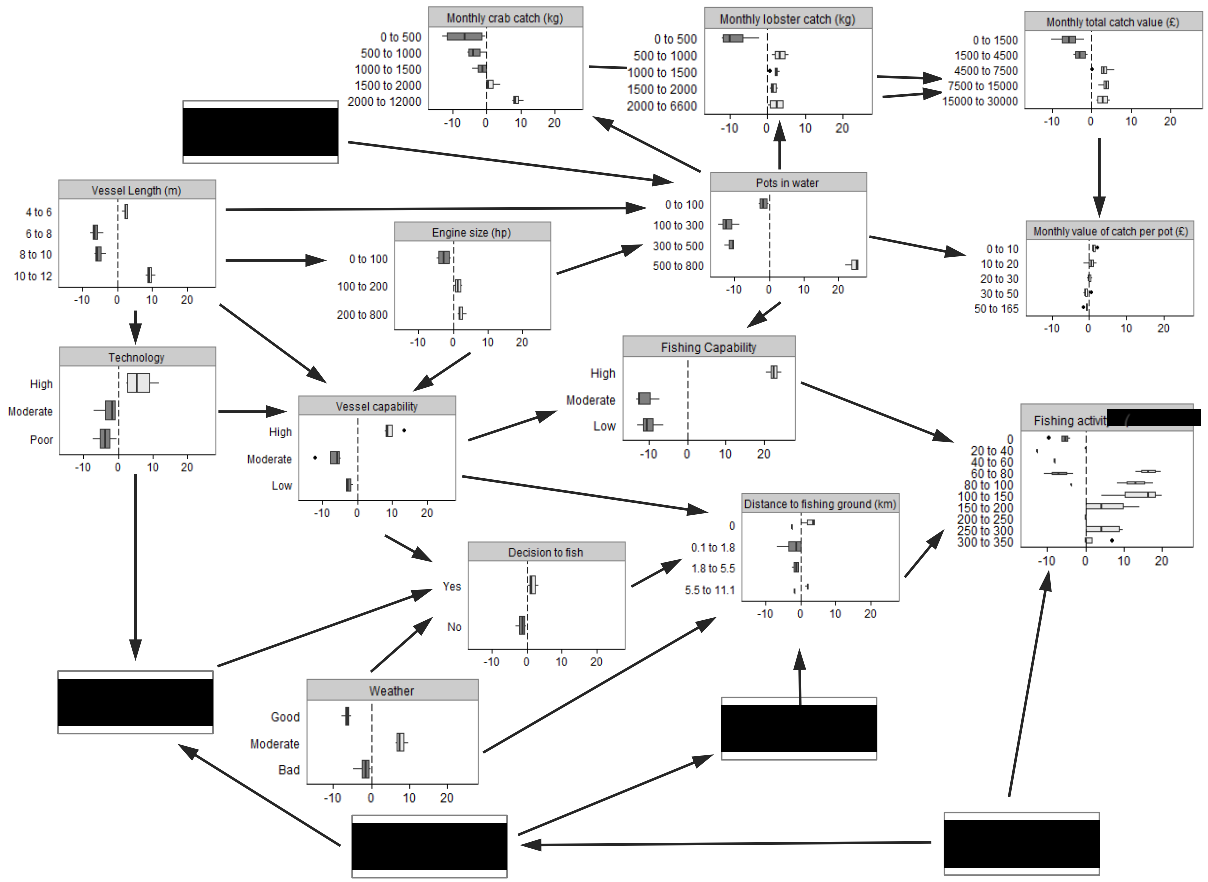

[redacted]
Monthly crab catch (kg)
0 to 500
500 to 1000
1000 to 1500
1500 to 2000
2000 to 12000
Monthly lobster catch (kg)
0 to 500
500 to 1000
1000 to 1500
1500 to 2000
2000 to 6600
Monthly total catch value (£)
0 to 1500
1500 to 4500
4500 to 7500
7500 to 15000
15000 to 30000
Vessel Length (m)
4 to 6
6 to 8
8 to 10
10 to 12
Engine size (hp)
0 to 100
100 to 200
200 to 800
Pots in water
0 to 100
100 to 300
300 to 500
500 to 800
Monthly value of catch per pot (£)
0 to 10
10 to 20
20 to 30
30 to 50
50 to 165
Technology
High
Moderate
Poor
Vessel capability
High
Moderate
Low
Fishing Capability
High
Moderate
Low
Fishing activit[redacted]
0
20 to 40
40 to 60
60 to 80
80 to 100
100 to 150
150 to 200
200 to 250
250 to 300
300 to 350
Distance to fishing ground (km)
0
0.1 to 1.8
1.8 to 5.5
5.5 to 11.1
Decision to fish
Yes
No
Weather
Good
Moderate
Bad
-10
0
10
20
[redacted]
[redacted]
[redacted]
[redacted]

Fig 5. Mean seasonal percentage change between 2004-2009 and 2010-2014 of all variables, driver effects indicated where these were significant. Dashed line within nodes shows zero percent change. Categories for nodes which did not show changes over time were not displayed.

4. Discussion

~~The Northumberland shellfishery has been reported to have the highest vessel sightings per unit effort in the UK (Vanstaen & Breen 2014) and potting effort has increased substantially between 2004-2014 (Stephenson et al 2017). The present work, using cost-effective multidisciplinary data in BBN models, provides further understanding of this economically and socially important Northumberland pot-fishery.~~ BBN models, contextualised with fisher interview data, have clearly identified socio-economic, environmental and technological drivers of changes in pot-fishing effort distribution in Northumberland, as well as changes in these drivers between 2004-2009 and 2010-2014. ~~Although, not exhaustive, drivers were selected based on expert elicitation, model variables were populated with a range of data types and were deemed to accurately explain Northumberland pot-fishing effort distribution (Czembor et al 2011, Naranjo-Madrigal et al 2015).~~ Below we discuss the importance of these drivers and their interactions, the effectiveness of current management of the pot-fisheries and make recommendations for future studies.

4.1. Drivers of fishing effort distribution

As in these pot-fisheries (Turner et al 2012) and those elsewhere (Acheson & Brewer 2003), the putative drivers of pot-fishing activity varied seasonally (Table 3). The distance from shore that fishermen were observed fishing (*distance to fishing ground*), the proportion of days that fishermen chose to leave port (*decision to fish*), the proportion of days which had good, moderate and poor weather (*weather*) and the perceived abundance of lobster and crab (*target abundances*) varied the most between seasons (Table 3). Seasonal changes in these variables are linked: *distance to fishing ground* and *decisions to fish* varied because of differences and interactions in *weather* and *target abundances* between seasons (for further detail see Table A1). Broadly, fishing effort was highest in summer and distribution was concentrated inshore because lobster were perceived to be present on inshore rocky reefs in high abundances and fishers could leave port a majority of days because of clement weather. Conversely, fishing effort was lower in winter months and distribution was dispersed, because fishers were restricted in the number of days they could safely leave port and targeted grounds further from shore in deeper water in order to avoid damage to their pots and maximise their catch during spells of poor weather (Table A1). Contrary to some other fisheries, where weather primarily determines the maximum safely navigable distance (and therefore limits the size of the available resource space) (Daw et al., 2011), Northumberland pot-fishing distribution has also been strongly governed by other factors such as target abundance and catch (Turner et al 2012). The majority of pot-fishing vessels in Northumberland have a maximum safely navigable distance beyond the >6NM NIFCA limit. The distribution and maximum safe navigability for the fishery, including effort and spatial distribution outside the 6NM limits of the NIFCA district, is scarcely known and would be of benefit for managers (NIFCA pers. comm.).

Values and distributions of nodes varied seasonally but the rank order of their influence on the end node *fishing activity* did not greatly vary between seasons. The five most influential nodes across all seasons were *distance to fishing ground, decision to fish, habitat type, weather* and *vessel capability* (Table 4). Fishers confirmed the importance of these variables – which were populated using quantitative data unrelated to fisher interviews – in determining levels of fishing effort and distribution during interviews. The influences and interactions of habitat type, climatic conditions and fishing ground choice on fishers' behaviour were discussed at length by fishers (Table A1, biological drivers), who also confirmed that larger vessels had higher fishing effort and fewer restrictions on their distribution compared to smaller vessels, explaining the high degree and rank of *vessel capability* in the sensitivity analysis (Table A1, fisher typology).

4.2. Drivers of spatio-temporal change in fishing effort

Potting effort distribution (pots.month^{-1}.km^{-2}) increased substantially in the study area between 2004-2009 and 2010-2014 (Fig 2) and for the first time temporal changes in drivers of this is illustrated. A combination of changes in fleet composition and fishers' behaviour probably best explain the observed increases in effort.

The variables *fishing capability* and *pots in the water* both increased in their higher categories (Fig 5) as well as having a much greater influence on *fishing activity* in models for winter and summer in 2010-2014 compared to 2004-2009 (Table 4). The increasing importance of these two drivers on the end node *fishing activity* is explained in the BBN model by technological changes of the active fishing fleet (Fig 5). Broadly, the proportion of vessels classified as having high *vessel capability* increased substantially during the study period (Fig 5). This was due to a combination of an increasing proportion of fishing vessels >10m with larger engine sizes, and concurrently, an increased uptake by the majority of fishers – including those with smaller vessels (6-10m) – of improved fishing technology, including GPS and sonar, better vessel layouts and hydraulic pot rollers (Fig 5). In turn, these high capability vessels have also been able to fish a greater number of pots (*pots in the water*, Fig 5) resulting in a large increase in the proportion of vessels classified as having high *fishing capability* (>20% increase, Fig 5). Finally, these high capability vessels can leave port and operate in harsher weather conditions, increasing the number of fishing days available throughout the year (increasing in proportion of fishers in category 'yes' of *decision to fish* node by ≈2%, Fig 5). These small changes can result in unexpectedly large changes in fishing effort. For example, ≈2% change in number of fishing days observed between T1 and T2 across the fishing fleet in 2014, would result in a mean increase of approximately 646 pots.month^{-1} or 7752 pots.year^{-1}. Although fishers frequently mentioned rapid changes in technology on-board fishing vessels over the last 15 years during interviews (i.e. better vessel layouts, larger pots and hydraulic pot rollers), quantitative data on these technological aspects are currently not available.

Although not illustrated in the BBN models, fishers stated during interviews that the increasing uptake of improved navigation technology and more accurate weather forecasting had enabled fishers to target specific areas or broadscale habitats opportunistically. The fishers considered that this meant increasing fishing efficiency and number of days at sea (Table A1), in-line with reports from other static-gear fisheries (Acheson & Brewer 2003, Brewer 2010).

Non-technological factors may also have contributed to the observed increase in potting effort. Traditionally the Northumberland fishery has been a mixed and seasonal fishery, with an array of species caught using different gears throughout the year. For example, salmon (*Salmo salar*) was targeted using drift nets from June-August; nephrops (*Nephrops norvegicus*) and white fish (e.g. cod, *Gadus morhua*) using trawls in winter; and lobster and crab using pots in summer. However, declines in stocks of finfish and nephrops and the increasing operational costs of maintaining and participating in these fisheries may have resulted in many fishers solely fishing in the less regulated pot fishery targeting high value lobster on a full time basis

(Acheson & Brewer 2003, Turner et al 2012, Molfese et al 2014). Although the number of active vessels in the district per year has not increased, fishers may be devoting more time to fishing lobster full time and therefore increasing their effort (Table A1, Mixed fishery).

Fishing is primarily an economic activity (Andersen & Christensen 2005), and the cost of fishing was mentioned throughout fishers' interviews, including when discussing other non-economic aspects of the fishery; this relates particularly to technological aspects of the fishery (e.g. vessel size, fishing gear and navigational equipment) because these are intrinsically linked to investment, risk and cost. Fishers were not willing to provide data for fishing costs and therefore it was not possible to calculate profitability. However, during interviews fishers stated that they had considered increasing catch because of the increasing fishing costs and stagnating crab and lobster market prices, as in some other studies (Abernethy et al 2010). Increasing costs of fishing in Northumberland have included increases in permit, new fishing gear, crew and fuel costs (Table A1). Landings for both lobster and crab increased between 2004-2009 and 2010-2014 (*monthly crab catch* and *Monthly lobster catch*, Fig 7), in particular, large increases in landings of both species were observed for vessels 10-12m. However, prices paid for crab and lobster landings by wholesalers have largely remained the same for lobster and have slightly increased for crab in each season between 2004-2009 and 2010-2014 (Fig 6). Although the *monthly total value of catch* increased between 2004-2009 and 2010-2014, the *monthly value of catch per pot* (a measure of efficiency) did not differ between these periods (Fig 7). Because profitability was not measured here, it is unclear whether increasing costs of fishing have increased effort levels, although this was frequently mentioned by fishers during interviews and is likely to be an important driver for increased fishing activity.

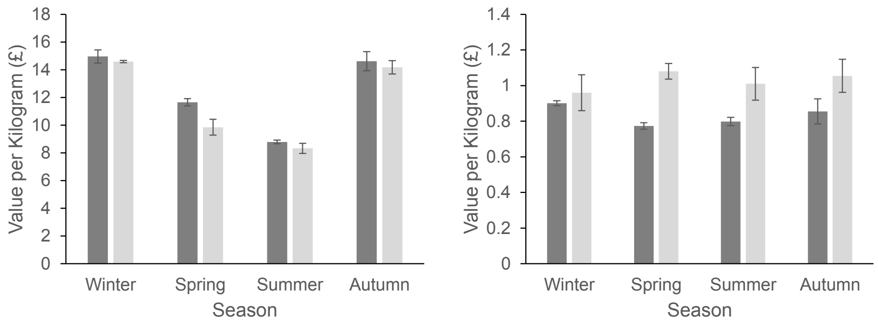


Fig 6. Mean seasonal lobster prices per kg for 2004-2009 (dark grey) and 2010-2014 (light grey). Prices were adjusted for annual inflation to reflect 2014 values. Data provided by NIFCA.

4.3. Fisheries management

4.3.1. Current Management

There are currently few management measures in place for the pot-fishery in Northumberland. However, each fishing vessel may only legally fish a maximum of 800 pots within the NIFCA district (NIFCA, 2014). This management measure was introduced in 2009 and was incorporated in the BBN model as absent in 2004 – 2009 and present in 2010-2014 (*pot limitation*, Fig 4). However, because no fishing vessels were recorded as fishing more than the 800 pot limit prior to the management measure in 2009, the node *pot limitation* had no influence on *fishing activity* (Table 4). The influence that this management measure has had on the number of pots each vessel owns remains unclear in the BBN model. Fisher perceptions of the efficacy of this management measure were mixed. 68% of fishers from the quantitative interviews stated that the limitation had not personally affected their decision on how many pots they owned (Table A1). However, 32% of fishers stated that they had increased the number of pots they owned in light of the pot limitation and 24% of fishers interviewed stated that they had bought a second vessel in order to “have another allocation” of inshore pot quota (Table A1). This trend in fishers moving towards management limits has also been observed in other pot-fisheries with similar pot limitations (Acheson & Brewer 2003). This increase in effort was attributed to fishers’ change in perception of the amount of gear they were allowed or expected to fish (Acheson & Brewer 2003), as well as the increasing cost of fishing (Table A1, Cost of Fishing).

4.3.2. Future work and scenarios for management

An advantage of BBN modelling is the ability to evaluate risk and uncertainty through simulated scenarios by modifying values in nodes of interest to investigate possible effects on end nodes (Naranjo-Madrigal *et al.,* 2015; Stelzenmüller *et al.,* 2010). The modelled outcomes of these management scenarios would only be an indication of possible effects and further work would be required to validate these models. However, the increasingly accessible large-scale multidisciplinary data sets collected for routine enforcement or monitoring purposes make BBN modelling a robust and cost-effective method (Landuyt et al 2013). In addition, data used to populate BBN nodes can be updated (i.e. through further ground-truthing or acquisition of new datasets)(Gonzalez-Redin et al 2016, Landuyt et al 2013). This allows models to be improved as new information becomes available making it an adaptable tool for monitoring of policies (i.e. their effectiveness) and for informing adaptive management strategies (Naranjo-Madrigal et al 2015, Prato 2005). Several management scenarios could be investigated using the present data and BBN model (Table 5) and may be more widely useful for other UK inshore fisheries.

Table 5. Possible future investigation: Northumberland pot-fishery BBN management scenarios.

Management measure	Description	Considerations and limitations
Vessel length limitation	Only vessels ≤12m are permitted to pot-fish in the NIFCA district. Results from the present work suggest that *vessel capability* is an important driver of *fishing activity:* the number of larger vessels (10-12m) operating in the district increased between T1 and T2 and accounted for a large portion of the fishing activity in the district. Scenarios investigating the effects of further limiting the maximum length of vessels on fishing effort in the NIFCA district could be undertaken by manipulating values for node *vessel length*.	Care should be taken when interpreting results from this scenario because of factors not taken into account in the model in its present form. For example, this may simply displace effort of larger vessels outside of the NIFCA district (>6NM from the coast), little information is available on current use or the implications of increased activity in these offshore areas, including possible in-direct effects offshore potting may have on inshore stocks (see sustainability of stocks in Table A1). Fishers abilities to change their vessel lengths and layouts is unknown at present. However, during interviews fishers discussed some of the adaptations to fishing vessels they had observed in order to circumnavigate regulations, e.g. large vessels (10-12m) being reduced in size (9.99m) in order to avoid having to comply with increased legislation of vessels 10-12m. These vessels will have the same width and similar fishing capacity as their 10-12m counterparts.
Limitation to the number of fishable days	Presently, the number of days fishers spend at sea is limited by climatic conditions. However, management scenarios limiting the number of days fishers could land crab and lobster could be tested by manipulating the node *decision to fish*.	If days at sea were to be limited, fishers may simply purchase larger pots that can soak for longer periods of time and therefore require fewer fishing days (Table A1).

Area exclusion / zonal management	Currently there are two protected areas in the NIFCA district: The Coquet to St Mary's Marine Conservation Zone and the Berwickshire North Northumberland coast European Marine Site. Potting is currently permitted within these areas but this is currently under review (MMO 2012). Exclusion of potting vessels in these areas could be simulated and changes in fishing effort of the remaining available NIFCA district investigated using GIS BBN analysis (for examples see Stelzenmüller *et al.,* 2011).	For this type of BBN analysis, all data used to populate the model must have a spatial component. High resolution habitat data used here was intrinsically linked to locations (resolution of 500x500m), however, differences in climatic conditions between locations within the NIFCA district are difficult to estimate at this small scale. It is possible to associate non-spatial data to locations in the study area if assumptions are made. E.g. vessels from Blyth do not fish close to Amble. Although this assumption is based on qualitative data, the low resolution of the resulting spatial data may mean they have little influence on the model. Alternatively, fisheries exclusion scenarios could be investigated using only variables that already have a spatial element by reducing the size of the BBN model presented here.

5. Conclusion

Difficulties in analysing multi-disciplinary data – which are often collected at different scales and formats – were overcome through BBN modelling of an exceptional data set collected for enforcement purposes by local managers. As in several other studies, seasonality in Northumberland pot-fishing effort and distribution was observed. However, within this setting, changes in fishing technology and fleet composition are likely to have driven the increases in fishing effort observed. Economic and social considerations such as the stagnating price of landings and decline of the mixed fishery may also have contributed to increased fishing effort, although the influence of these on fishing effort and distribution and on other socio-economic nodes remains poorly quantified. The flexible nature of BBN decision models allows new data to be incorporated when available and the effects of a range of possible management scenarios on fishing effort and distribution to be explored in future work.

6. Supplementary materials

6.1. Summary results of fishers' quantitative interviews and semi-structured interviews

Table A1. Drivers of fishing effort and distribution in Northumberland and temporal changes (2000 – 2016) based on quantitative interviews of fishers (*n* = 25, approx. 60% of active fleet, June 2015) and semi-structured interviews (approx. 1.5 hours per interview) with key informants (*n* = 6, approx. 10% of active fleet, May 2016). Drivers were categorized into themes: Environmental (green), Fisheries management (orange), Economic (yellow), Social (blue), and Technological (grey).

Driver	Description and interactions with other drivers	Perceived importance	Temporal changes
Habitat type	Fishers demonstrated detailed knowledge of geophysical properties of the seabed ("rock, sand, mud, mixed cobbles/reef, shelly ground") and some knowledge of benthic communities: "sea urchins and kelp get washed into pots on hard ground and in the intermediate zone (reef edges) you get coal, stones and empty whelk shells"), although only the geophysical aspects of habitat were said to be used for targeting catch. Habitat is determined using a mix of experience, including from other fisheries ("I've fished for a long time (trawling and potting) so I know where mud, and sand end and rock starts and you've always got an intermediate zone where there's gravelly bottom and stones on and that's where you'd tend to see someone scallop dredging") and increasingly echosounder and acoustic ground discrimination systems (AGDS). In summer, 72% (*n* = 18) fishers said they targeted primarily hard reef, whereas in other seasons this declined to 64% (*n* = 16). Although rocky reefs were described as being the primary target in the NIFCA district, all other habitats were also targeted: "smooth (soft sediment), mixed cobbles/reef and shelly ground habitats". Habitat choice was highly dependent on target species and climatic conditions (see climatic conditions below): "It's that different (the	Description of habitat targeting was discussed in detail by all fishers in the semi-structured interviews. Habitat type was considered a key consideration for fishing ground choice but in combination with climatic conditions and target species behaviour.	Although habitat targeting behaviour of fishers has not changed over the last 15 years, the ability to accurately target a specific habitat has increased with the rising use of echosounder and GPS. Habitats which may have particularly high catches may be exploited at higher levels due to the increasing ease that these can be accurately located with GPS and sonar. In addition, the repeatability now offered by these technologies has allowed "virgin or less exploited ground" to be targeted further offshore (see technological drivers). Some fishers viewed this as having "ruined fishing, anybody can do it now", whereas others still maintained that "you can't replace experience" for successful catches, having observed fishers with low catches despite having expensive echosounder: "you see some people with Roxanne (AGDS) come and they smack their gear right over this peaky bottom (high complexity reef) and they haul up for bugger all, all of it for nothing, because they're (the lobsters) aren't moving on that bottom."

	climatic conditions) that on a weekly basis you might fish all these habitats”. Lobsters were caught in high numbers on hard reefs with high complexity, but only under the calmest of weather conditions, in worse weather, they were described as easiest to catch on mixed ground on the edges of reefs (boulders, sand, shells, reef patches). Crab were discussed as being targeted on softer ground, although these can be caught on all ground types and may form a significant portion of the landings as by-catch when targeting lobsters. Decision of which habitat to target was often described as being a mixture of past experiences and short term success through explorative potting “You shoot them (pots) on east and west, start on rock and maybe go 10% on the mud, and then leave it for a couple of days. Then you’ll haul and you’ll see and you’ll know exactly what part of the ground you’re wanting to be on for the current conditions. So then when you do start shooting them North and South (the norm in Northumberland) on that strip that was successful. It’s like you’ve got a 3d picture in mind of the bottom.”		Due to climatic conditions playing a large role in fishers targeting behaviour of habitats, seasonal patterns were often discussed (see climatic conditions below).
Target species	Landings data showed high catches of lobster in summer and higher crab landings in winter, however, this was not perceived to be reflection of fishers targeting behaviour but rather the availability of target species due to climatic conditions, biological cycles and habitat type. Most fishers stated that they mainly targeted high value lobster all year round but primarily caught high numbers of these during summer. “I target lobster all year round but I don’t catch them all year round”. Crabs were often caught in high numbers as by-catch and were described by some as a way of bringing in extra money on top of lobster catches (see investment and risk): “I don’t target crab at all in the summer, any crab is bycatch”. Some specialised vessels were described as targeting primarily crab but these were often larger vessels fishing outside the NIFCA district (see fisher typology). Fishers demonstrated a high degree of knowledge on target species behaviour, gained through experience, describing conditions when	The choice of target species was not a major contributing factor for the majority of fishers with other drivers playing a larger role in the fishing ground selection and effort levels. Lobster was primarily targeted all year round, climatic conditions permitting.	Fishers did not discuss any particular changes in their target species behaviour: “On a historical basis these numbers (target catch by season) are fairly accurate”. There were some seasonal changes with more crab caught in winter and some vessels that have specialized somewhat in targeting crab further offshore outside the NIFCA district although these were a very small minority (estimated at 4–5 vessels in Northumberland).

	"lobster will just give themselves up (go into the pot)", and when crab would be caught "You can be fairly indiscriminate when crab fishing, once you get further offshore, the ground gets smoother and when crabs want to crawl and the conditions are right as long as you bait those pots you'll catch crabs, you've got to be more discriminant when catching lobster."		
Biological cycles of target species	Fishers discussed the difference between catchability and abundance. Fishers targeted areas where, in line with climatic conditions, target species were actively feeding and therefore more catchable. Respondents said that crab were likely to migrate seasonally, found in greater abundances close to shore in shallow water in summer and moving eastwards towards deeper waters offshore in winter. "There's vast areas, at certain times, where you would be wasting your time for crab. Although, I can't say they're not there but they're not available, but I don't think they are there because crabs are very mobile, I think crabs are more mobile than lobsters." In contrast lobster were thought to be more site dependant and may be caught in the same area all year round under the right climatic conditions. "Lobster are more indigenous, to the point where you get v-notched lobsters coming back that have been dropped 5 miles away and they come back to a piece of ground. And you'll catch that lobster in the same place for 3 years and you know it's the same lobster." Other respondents echoed this view: "To me, they're there (lobsters) all the time but they're not feeding. If they're not feeding or moving then they're not going to go into your pots."	Perceptions of biological cycles and species behaviours were considered an important driver of fishing ground selection, with some fishers believing they "follow the stock" out to deeper water and all fishermen discussing the catchability of target species being dependant on climatic conditions.	Biological cycles and behaviour of target species were not perceived to have changed between 2004 and 2015 but seasonal changes were described at length.
Climatic conditions	Climatic conditions were described as a combination of weather, tidal height, wave exposure and water temperature. These are all closely linked to seasonal patterns, with harsher climatic conditions in winter and milder climatic conditions in summer. Climatic conditions are perceived to affect both the biological cycles (see	Climatic conditions were highlighted at several occasions by all interviewees as having a very strong influence on	Climatic conditions were not perceived to have changed between 2004 and 2014, although seasonal changes and unusual climatic conditions were discussed at length; "You get winters where lobster don't hole up because it's the right conditions (stay in one place) so you could get a situation where you turn around and

biological cycles) and behaviour of target species (target species) as well as fishers' choice to target grounds (see water depth).

The weather, tides, wave exposure and water temperature were key drivers of fishing ground choice. High wind speeds and adverse weather limited the number of days that fishers could leave port to go fishing. In calm weather, higher water temperatures and low sea states (most frequently encountered during summer), lobsters were predominately targeted on shallow inshore reefs, although big tides could result in fishers fishing slightly deeper: "I'll drop down a few fathoms to get out of the sediment" from tidal movement which resulted in lobsters "holeing up" and not feeding (thus not being caught in pots). In adverse weather, with high sea state and lower temperatures, provided that it was suitable to leave port, fishers targeted areas further offshore where the water depth ensured that conditions on the seafloor would be less affected by climatic conditions. "As soon as there's any sign that there's adverse conditions, they'll (lobsters) will move and eventually they'll end up in the peripheral zone of the hard ground (which) is the most productive." Fishers choice of ground, distance from port and their decisions to leave port were also heavily affected by their vessel size (see vessel capability), with smaller boats fishing fewer days in harsher climatic conditions and larger boats being able to fish in up to about 25knots of wind: "There's a few (boats) over 10m, fisherman X has a 12m boat and nothing stops him"

Due to the close link between weather and fishers ability to leave port or move gear safely, fishing effort is highest in summer with fishers aiming to haul their pots every 24 hours, whereas in winter it is lower and more variable with fishers hauling pots on average every 3 – 7 days. "It (the number of days pots can be hauled) varies with the weather and availability of catch. You haul them whenever the opportunity arises"

Fishers all described the increasing accuracy of weather and sea state forecasting which gave them a greater ability to target productive grounds for any particular climatic conditions with the increased confidence that they would be able to move to other

their choice of fishing ground and effort levels. 76% of fishers (*n* = 19) in the quantitative interviews stated that this was the most important driver of potting effort distribution.

start targeting lobster instead (of mixed crab and lobster catches)"

Accuracy in weather and sea state forecasting was perceived to have increased from 2004 – 2015 and allowed fishers to target optimal grounds and have higher returns, as well as a greater ability to plan ahead and take advantage of shorter weather windows. These advances were also perceived to have reduced damage to their gear as well as to have increased landings.

	grounds in time if these changed (see water depth): “I would say you’ve got something like 80% reliability on 3 – 5 day internet forecasts and you can position your gear where you think it’s going to be most effective. Whereas in the past you would get a shipping forecast in the morning and you’d think that’s not too bad, then you’d get one at dinner time and it would be 6 – 8 gale NE (bad weather) and you’d have to ring around and get your crew to belt down, get the boat before it was dark and start shifting gear and you could never take it where it would fish best, you just had to take it where it was going to be safe. It’s (weather forecasting) has had a massive influence on the boats ability to use weather to your advantage.” Climatic conditions were also frequently discussed in relation to damage to fishing gear (see water depth).		
Water depth	Water depth was frequently described as an important consideration for selection of fishing grounds because under various climatic conditions (see climatic conditions) target species were more or less catchable at various depths. With increasingly poor climatic conditions deeper fishing grounds were seen as the most productive, whereas in clement climatic conditions shallow waters were considered the most productive. In addition, water depth was a key consideration for gear damage (which was perceived as an increasing cost and was therefore of importance, see cost of fishing) and fishers described mitigation techniques to limit damage to gear such as only fishing in “the safe” (deeper grounds) and avoiding the “the dry” (shallow reefs). Smaller vessels which were perceived as more adaptable due to having less pots in the water frequently moved their gear on to grounds of various depths, sometimes several times a week, in order to target the “most productive grounds for the climatic conditions”. “If you get weather like this (raining and waves), 5.5 m tides, 7 – 8 knots easterly and 2.5m swell, you want your gear in at least 22 fathoms (approx. 44 m), nearly on the mud, you’d probably get good returns there. If you had them on the dry (shallow water) you’d lose	Water depth was not perceived as a driver of site selection but rather an important consideration given climatic conditions and biological cycles/ behaviour of target species.	Depth of fishing was not perceived as having changed as it was governed by climatic conditions. Variability in years was discussed, with many of the interviewees discussing mild winters that allowed high catches of lobsters on the shallow inshore reefs that would usually not be targeted due to bad weather. “You get years when in February you’ve got 4 weeks where you can walk around in a t-shirt. If you know that’s coming then you know the high pressure is going to sit there with westerly winds 11 – 12 degrees you can bring all your gear in and shoot it as close to the shore as you like. And the lobsters will move, they will be lulled into a spring frenzy and you’ll get 2 – 3 weeks of excellent fishing”

	them (pots), if you had them just where they were safe, 7 – 8 fathoms (14 – 16m), there would be nothing in them, stuff just holes up and wouldn't move (lobsters don't go into pots)."		
Sustainability of stocks	Although there were no questions on the sustainability of stocks in the semi-structured interviews this was mentioned by all respondents. Fishers generally thought that stocks were fished at a sustainable level inshore "you get a sort of balance if you caught all the lobsters you would stop fishing. The perfect place is somewhere in the middle where recruitment roughly equals catch. And without any outside influence I don't see how you would get anything other than that, it's a logical conclusion", but some had reservations about exploitation, including the more recently fished offshore grounds. "there's no buffer zone (the distance pot fishers would leave for mobile gear fisheries so as not to lose equipment) now so you go to bits of ground that have never been touched (by pot fishers) with big lobsters on it and lots of crabs, but the problem is it's not a ground that has been traditionally recruited every year, you know, it hasn't needed it, it's been stagnant, when you fish that (ground) it changes the seabed and it has a much more profound impact on (the stock on) those grounds than on grounds that have been fished for generations" Management regulations aimed at maintaining stock levels were perceived with some level of scepticism although many acknowledged that these were likely necessary in order to stop "some (fishers) spoiling it for everyone", especially larger vessels (10 – 12 m) which were thought would "have 2000 pots in the dry (<10 m) and they would just strip fish it because they know that when it's finished they can just move further out" whereas the smaller vessels would not be able to. Fishermen also mentioned how other fishing methods had changed "the seascape", discussing the decline of finfish and how this had resulted in a greater number of fishers potting fulltime (see reduction of the mixed fishery).	There was some evidence that fishers considered the sustainability of the stock when selecting fishing grounds: "It's not been left fallow so I won't catch much" but this may have been more about having poor catches in those areas. Sustainability of stocks was not considered important for individual fishers' fishing effort: "If your catch is poor, you have to go out and fish more to make your money"	Fishers perceived that shellfish stocks were, and had been, stable over the past 15 years. However, occasionally fishers mentioned the possibility that offshore fishing may be reducing stock levels inshore. "Further offshore, the ground isn't as hard as inshore but you can find big lobster where they haven't been fished before. The fears is that this is the breeding stock (for the inshore)".

Regulations	The pot limitation was perceived to have mixed effects on fishers' behaviour. Fishers did not think that the pot limitation had resulted in a decrease in fishing activity as only a handful of vessels were fishing up to the limit before legislation was implemented. 68% of fishers from the quantitative interviews stated that the limitation had not personally affected their decision on how many pots they owned. However, 32% stated that they had increased the number of pots they owned in light of the pot limitation and in some cases (6 out of the 25 fishers interviewed) stated that they had bought a second vessel in order to "have another allocation" of inshore pot quota. Reasons for this increase in effort were stated as: "For some people it became a target, they would never have dreamt of having that many (pots before the limitation) but because they were allowed that, that's what they had" but also in order to stay abreast of the increasing cost of fishing (see cost of fishing). The pot limitation was often discussed as being "good in a way", although most fishers saw these regulations as another way of their industry "being controlled more". Regulations on other fisheries, such as quota for the cod fishery and reduction in the number of licenses for the salmon fishery were described as being one of the reasons that there had been an increase in the number of shellfishers full time as this had fewer legislation, more consistent catches, and was perceived as an "easier way of life" than other fisheries. The lack of regulation for shellfisheries offshore was frequently discussed, with many fishers discussing the possibility of finding "virgin ground that had big lobsters".	Regulations were not perceived as an important factor affecting choice of fishing ground in the NIFCA district although it is clear that some fishers have started fishing outside the district where no pot limits are in place. The pot limitation was perceived as either not affecting fishers or indeed increasing the number of pots fishers' owned, and therefore the number of pots they fish. The extent to which the pot limitation is responsible compared with other drivers such as the cost of fishing is unknown.	The pot limitation was enforced in 2009, and some changes occurred in fishing effort and potentially fishing effort distribution (offshore) although these changes are tentative and fishers did not place much emphasis on this. It is also clear that the decline of other fisheries due to regulations and decline in stocks has resulted in an increase in full time pot fishers in Northumberland (see decline of the mixed fishery).
Compliance	Compliance was perceived to be high due to enforcement "They (fishers) are virtually full compliance, and that's come about due investigations and prosecutions. It's a totally legitimate industry with totally declared earnings, and as with most industries, everything is known about it", although with regards to the pot limitation several interviewees described that there was a very small minority of fishers	Compliance is not considered an important driver to fishing effort or choice of fishing ground primarily due to the offshore areas outside the	Increased compliance was described by two fishers, although others perceived that this had not changed over the last 20 years. "There's been loads of stuff gone on (enforcement) over the last 2 decades, so it's been the same"

	that were thought to fish over the limit (untagged pots “there’s boats fishing more than that. What are you going to catch? Just wrecking the future basically”). Although not against the law, fishers that purchased 2 boats to get twice the quota were perceived by one of the interviewees as “taking too much”.	NIFCA district being unregulated and accessible by the majority of fishing vessels, although with varying degrees.	
Cost of fishing	The cost of fishing was described as being dependant on the amount of money invested in the fishing operation (see investment and risk; fisher typology). One of the main running costs of fishing was fuel although this was perceived as “a consideration but not a governing factor” in fishers’ day to day decisions to fish or how far from port they would fish “if there’s nothing (lobster) at 10 mile, but I know there’s some at 20 mile I’ll go” (80% fishers, *n* = 20, ranked fuel price as the least important driver for fishing effort distribution) although for bigger boats it may be a more important consideration than for smaller vessels. “So if you’re talking about a vessel that fishes 30mi offshore, it would have an impact but not one that outweighs any of the other factors, it’s just the cost of taking part in the industry and most people with half a brain wouldn’t buy an outfit where more than 10% of its costs are fuel”. Unlike mobile gear fisheries where powerful engines which consume a lot of fuel are needed, potting vessels targeting inshore grounds were said to not need large engines (see travel time) and therefore use relatively little fuel. Increasing cost of gear (pots) was also frequently mentioned “you’ve got all your gear, like the pots, rope, all that’s went up in price” as well as changes in the consumer market affecting the price that fishers can sell catch: “Lobster have always been a premium product but at a £5 each I don’t think they’re a premium product anymore, you can pay a fiver for a pint of good beer in Newcastle”	The cost of fishing was perceived as an important factor as to whether fishing was a viable occupation but did not affect fishers days to day decisions to fish. Increases in the costs of fishing were perceived to be one of the major drivers for increased effort (see investment and risk)	All interviewees stated that the cost of fishing had increased for all fishers because “the price of crab and lobster has (in) no way matched the rate of inflation over the last 15 years….. (shellfish wholesalers) were paying £5 a stone of crabs in 1982 they’re now about £8 a stone. They (prices) haven’t even doubled in 30 years but the cost of fishing has quadrupled in 30 years.” In addition, other costs, such as fuel and the cost of gear have increased considerably at a quicker pace than the price of catch.
Travel time	Travel time to fishing grounds was not seen as a major driver of inshore fishing. “The boat we had before had a 400hp engine but the	Travel time was not considered an important	Travel time was not perceived to have increased for inshore fishing (within the NIFCA district), although it was acknowledged

	one we have now is 200hp. We get to places a lot quicker in the last one we also had more expenses because of the fuel.” Achieving high catches was considered more important. “It’s about following the stock, hope that you catch enough to cover it (the cost of fishing)”. For larger boats that fish offshore, travel time can be considerable and therefore they have invested in vessels with larger engines (see vessel capability).	driver for site selection or fishing effort.	that fishers travelling outside the district may spend longer at sea due to increased travel time.
Investment and risk	This is the amount of monetary investment into fishing operation, including investment in the vessel, gear, and shore based operations. In general fishers described that the larger the vessel size, the larger the investment, which in turn resulted in having to fish more in order to make a living (see typology of fishing).	The level of monetary investment in fishing was perceived as an important driver for fishing effort, with higher investment resulting in higher levels of effort in order to pay back loans.	Specific changes over time in investment levels were not discussed, although it was clear that interviewees knew fishers who had invested large amounts in the last 10 years.
Fishers interactions at sea	Fisher’s interactions at sea included negative and positive interactions. Negative interactions at sea were due to competition for space on the most productive grounds, which was frequently mentioned as well as territoriality with other ports. “they (fishermen) doesn’t want us there, so if I leave my gear and he knows where it is in the summer, then when I go back my pots have had the lines cut (resulting in not being able to locate the pots at the surface)” However, positive interactions were also mentioned for example, “fisherman X knows what he’s talking about. He knows where to fish. That’s the thing as well, you know when you see other boats, you think oh I’m in the right place here. Fisherman X is one of them, if I’m fishing alongside him I know I’m in a decent place.”	Fishers’ interactions at sea were not described as affecting fishing effort, however, competition may alter distribution of fisheries, with “marked areas” excluding fishers from high catch areas.	Fishers’ interactions at sea were not discussed as having changed over time (but see Turner *et al.,* 2012 for in-depth discussion on pot-fisher territoriality in Northumberland).
Experience	Success of fishing was often linked to high levels of experience. Although technology was now seen as allowing less experienced fishermen to enter the fishery, potting experience was perceived as being more important and allowed fishermen to increase their	Experience was perceived as one of the major factors affecting distribution (i.e. choosing the best location	Experience level amongst fishers was perceived to have increased due to better technology which allowed already experienced fishers to gain further insights. However, it was

	success further. "From what I've seen from their (inexperienced fishermen) performance it doesn't really outweigh experience. But it does give somebody the ability to partake in the industry without any experience whereas they wouldn't have been able to do that say 20 years ago".	for high catches, given the climatic conditions), however, this was not seen to affect effort.	made clear by several interviewees that experience did not necessarily equate to successful fishing.
Reduction of the mixed fishery	All but one of the interviewees discussed having started fishing targeting finfish for at least a portion of the year: "the fishery used to be more mixed with herring from August to September, sprats in the winter time, prawns and white fish the rest of the year". They described various reasons for focussing on the pot fishery fulltime including the decline of finfish catch, increasing fisheries management, limited finfish quota and an easier way of life. "My dad was sick of it, not catching the fish, and the paperwork that goes with it. So he sold that, (and) he got a smaller boat with the pots, because it's supposed to be an easy way of life". In addition, the reduction in the use of mobile gear, especially offshore, allowed areas which previously would not have been potted to be exploited successfully (offshore) for crab and lobster: "At one time 30 years ago you couldn't put a fleet out there because it would have been towed away by a trawler. It's only since the mobile fleet decreased that it was safe to actually put gear (pots) out there. And low and behold they found shellfish there, that I don't think anyone realised were there in the past."	The reduction in the mixed fishery was seen as an important reason for the increase in fishing effort as it is now the predominate method of fishing in the district with ex-trawling vessels converted to be able to pot. In addition, the dominance of the pot fishery has allowed previously unexplored ground to be potted therefore changing somewhat the distribution of fishing activity although this was for areas outside the NIFCA district.	There has been a clear change in the number of fishers that now pot fish full time all year round, although the majority of these changes may have occurred prior to the study period 2004 – 2014.
Vessel capability	Vessel capability was described as the vessels ability to fish. Vessel length and width were described as important factors affecting vessel capability because bigger vessels were able to carry more fishing gear and more easily integrate technological innovations such as bigger pots and pot rollers (see technological innovations). Engine size was not considered particularly important to vessel capability for potting vessels because, although larger engines allow quicker travel, this was only a consideration for a small portion of the fleet which travelled long distances offshore (outside the NIFCA district). Static gear fisheries were described as benefitting from	Vessel capability was perceived as an important driver for both fishing effort (bigger vessels were capable of fishing more), and fishing distribution with different vessels capabilities utilizing different fishing grounds.	Changes in vessel length and engine size were either described as being small or not at all by all respondents. However, vessel types were described as having changed over time "There were boats that were 33 – 36 feet so they were long boats but they didn't really have the fishing capacity because they were designed for beach launching, to be sea kindly, to salmon fish and pot as a supplementary activity, therefore because they weren't efficient they were phased out but because they were

	smaller engines as these cost less to run (fuel) and were not needed to tow heavy equipment such as those used in mobile fisheries. As most vessels from the last 5 - 10 years were considered to have GPS and sonar installed, these were perceived to have little bearing anymore on vessel capability, although these were discussed as having provided an advantage to large vessels which had them installed prior to that. Vessels with high capability were described as being able to fish in worse weather conditions which made these more advantageous for fishing further offshore and during the winter months. Smaller vessels were able to fish in very shallower water with more ease which during the summer months was where the highest catches of lobster were perceived to be. Fishing effort in relation to vessel capability was often discussed with high capability vessels able to fish a greater number pots throughout the course of the year due to their greater efficiency (See technological innovation: pot roller, larger pots, ability to hold more pots) and their ability to fish in a wider breadth of weather conditions and spend longer at sea. Fishing behaviour may change with vessel capability (see fishing typology). As vessel capability increases so does the cost of fishing (see cost of fishing), with larger more technologically advanced vessels requiring a larger financial investment, in turn resulting in fishers having to fish more in order to pay for the large investment (see cost of fishing).		bigger boats they were as costly to run and maintain as modern slightly larger boats can be". Vessel layout and adaption of technological innovation was frequently discussed as having increased in the district with the integration of these vastly increasing their fishing capability.
Technological innovation	Technological innovation in Northumberland included increases in use of positioning technology, various sonar technologies and changes in potting gears. Technological innovation was perceived as having allowed increased fishing effort. The vast majority, if not all commercial potting vessels in the NIFCA district were thought to have GPS and ecoshounder (in 2016). All respondents stated that having these technologies on-board made targeting productive fishing grounds more efficient (i.e. "GPS for	Advances in technology, although not available on all vessels, were perceived to have allowed increased catches and effort. It is unclear whether these are important to fishing distribution,	Changes in technology on-board fishing vessels have increased rapidly over the last 15 years although there was no quantitative data to back this up. This increase may be important and further research into this is recommended. For example, investigation of catch efficiency (soak time vs abundance) for different pot sizes would be useful as this is not taken into account when calculating CPUE or other management metrics but may alter these significantly.

	locating a fishing ground and returning to it at a later date" and echosounder for "easier judgement of ground" habitat type. These have also allowed for faster exploration for productive grounds as well as the ability to target previously overlooked small patches of reef. Pot rollers allowed quicker hauling as well as fishing pots of greater size, and less crew ("There's only me and another guy. The roller just lifts the (large) pots on-board for us. I'm just standing working the winch control"), although these could only be installed on vessels larger than 8 -9m (depending on width of the vessel), thus smaller vessels could not integrate this technological advance. "Any boat that can carry them (pot rollers) has got them. They're trying to fish as big a pot as possible (limited by the roller)". Pot size was also perceived as increasing and is thought to have allowed increased catches, longer soak times (which allows fishers to have more pots overall) and because these are heavier, fishers don't worry as much about adverse weather moving these and may in fact fish shallower than with other pots. "There's 35 of them in a fleet, they're basically like anchors, they're not moving. You have train weights at the end instead of anchors, but you don't really need them the pots are that heavy really."	although GPS and sonar may have allowed exploration of fishing grounds offshore outside the district where "there's no landmarks" (feature on land that helps fishers recognise where he/she is geographically).	
Fisher typology	Fisher typology refers to groupings of fisher strategies and behaviours. Although this may be seen as a social factor, it was described as relying primarily on vessel type. "Boats can be too big if fishing at the rock ends (shallow reefs) but offshore bigger, faster vessels have the advantage" Interviewees described many different strategies that were employed by themselves or by other fishers. 3 main fishing strategies (typologies) were broadly described by all interviewees. These are generalisations and in reality fishers may have behaviours and technologies that belong to more than one group: 1) Small "traditional" fishers (small vessels <8m, small engines <50hp, 200-500 small traditional pots, GPS, echosounder): fish	Fisher typology was largely categorized by fishing vessel capability and cost of fishing. Both of these were considered to be strong drivers of fishing effort and distribution.	Fisher typology was not thought to have changed, although whether the number of fishers belonging to these groups has changed remains unknown.

primarily within the district, without pot rollers and haul their pots as often as possible (every 24-hrs weather permitting). These fishers are very adaptable in effort and distribution as they have a small amount of gear - they can fish in shallow waters even in winter because they can move their entire fleets within approx. 2 days. Opportunistic with the weather, low cost of fishing, especially fuel but also have few crew (often no more than 1 deckhand, 1 skipper). These vessels, due to their adaptability may have high CPUE if skippered by experienced fishers although no quantitative data is available to investigate this further.

2) This group wasn't referred to in any particular way, but may be considered the norm in Northumberland. Mid-size vessels (8 -10m to avoid higher amounts of legislation but still have access to the 10m pool for whitefish and mackerel), GPS, echousounder (some may have AGDS, e.g. Roxanne) and mid-sized engines. They fish inshore in summer but move much further offshore in winter including frequently fishing outside the district (some may go further than 12NM). They may have pot rollers and larger pots enabling them to own (and fish) a greater amount of gear (600 – 800 pots in the district and 0 – 300 pots offshore) with longer soaks (2+ days, especially in winter).

3) Large "industrial" vessels (these are not industrial vessels in the typical sense but were described this way in order to convey the sense that a much larger operation was needed to run these vessels, including shore based operations): They are the biggest vessels allowed to pot in the NIFCA district (10–12m), have large engine sizes, more crew (1 skipper 2–3 crew), and usually require a large investment which results in having to fish intensively. The majority of these vessels have pot rollers and large pots. They may have 800 pots in the district and "maybe another 800 outside". They still fish inshore in summer (although maybe not as shallow as the smaller vessels) but may not fish all their gear inshore as it may take too long to move all their gear in adverse weather. They therefore tend to have a more risk adverse strategy and fish in the "safe" more often. They have the ability to fish 10–30 miles offshore to find areas with high catches (virgin grounds) and may stay out at sea longer

than smaller vessels (24–48 hours). The level of exploration outside the district is unknown as of yet. In general, these vessels were described as having lower CPUE than smaller vessels because of their increased effort and their less adaptable strategies.

6.2. Seasonal BBN models for T1 and T2

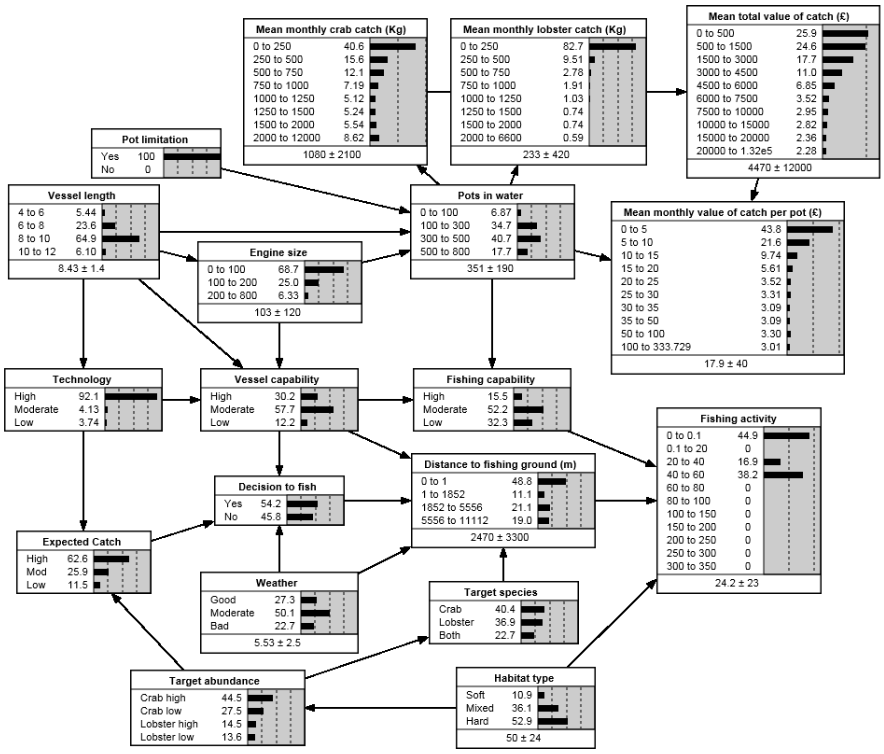


Fig 7. BBN model showing variables that affect fishing activity in Northumberland in winter at T1. Medians and standard deviations are shown for continuous data.

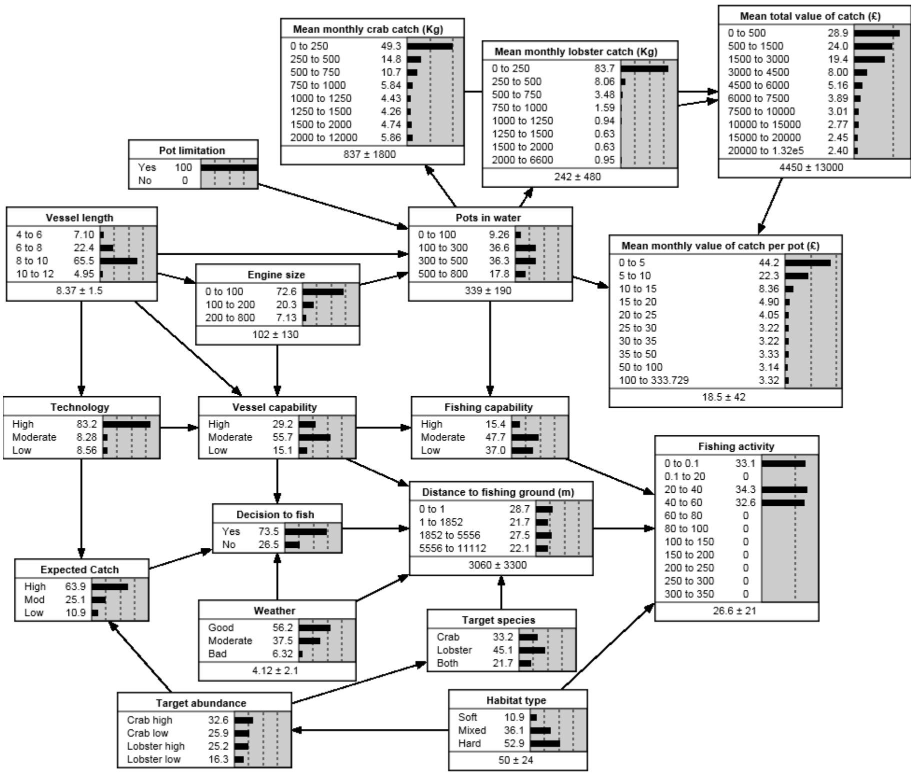


Fig 8. BBN model showing variables that affect fishing activity in Northumberland in spring at T1. Medians and standard deviations are shown for continuous data.

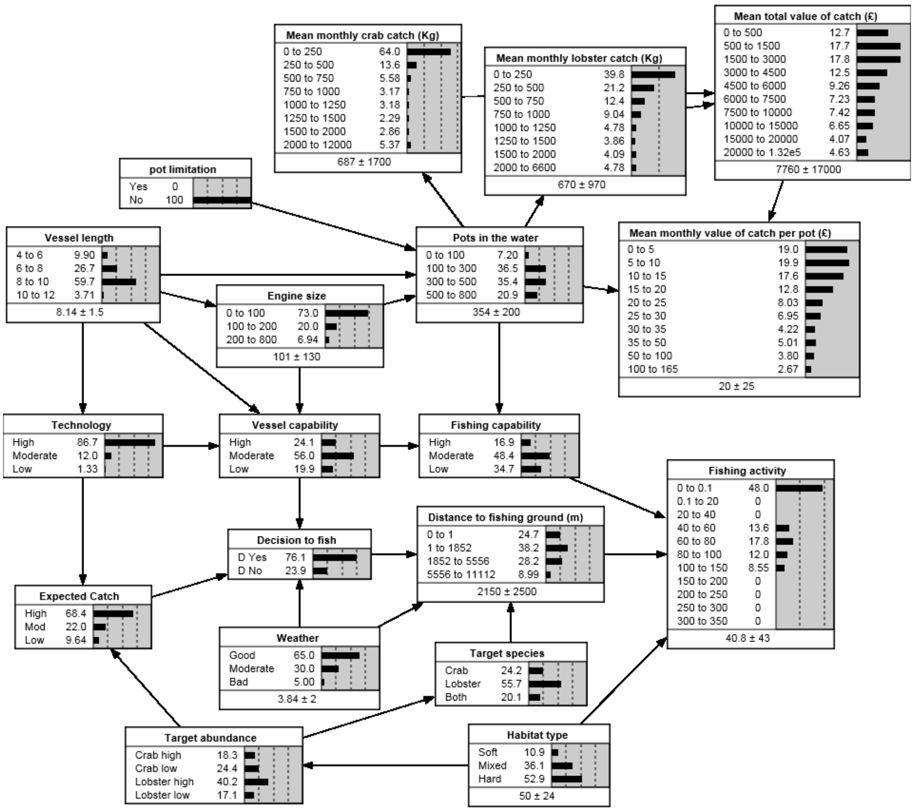


Fig 9 BBN model showing variables that affect fishing activity in Northumberland in summer at T1. Medians and standard deviations are shown for continuous data.

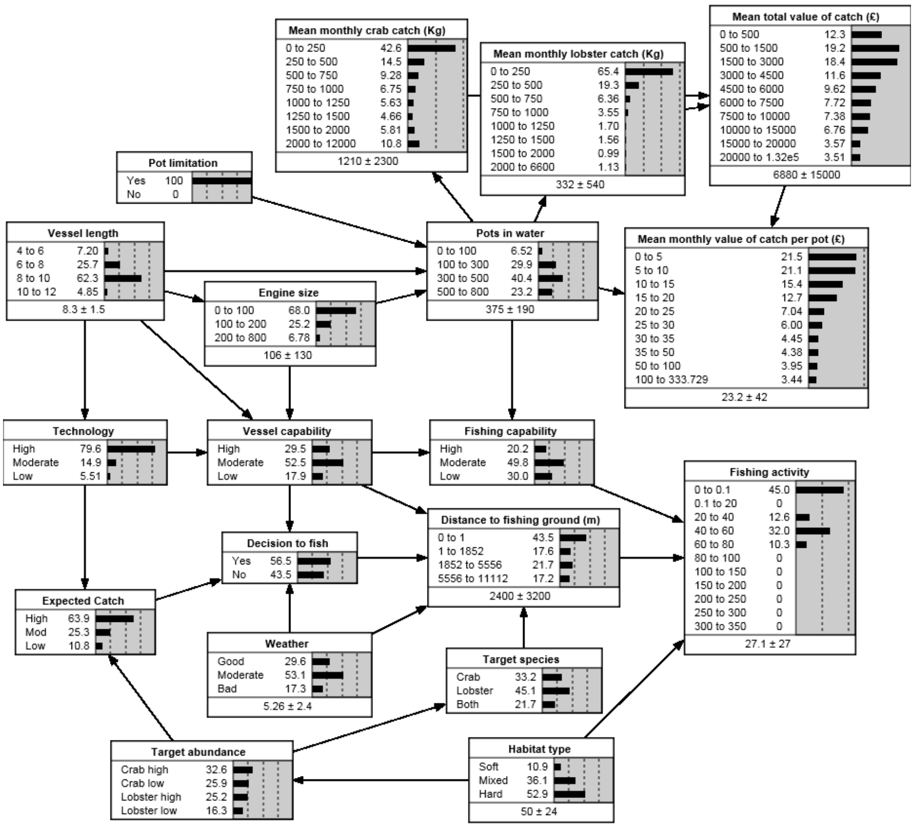


Fig 10. BBN model showing variables that affect fishing activity in Northumberland in autumn at T1. Medians and standard deviations are shown for continuous data.

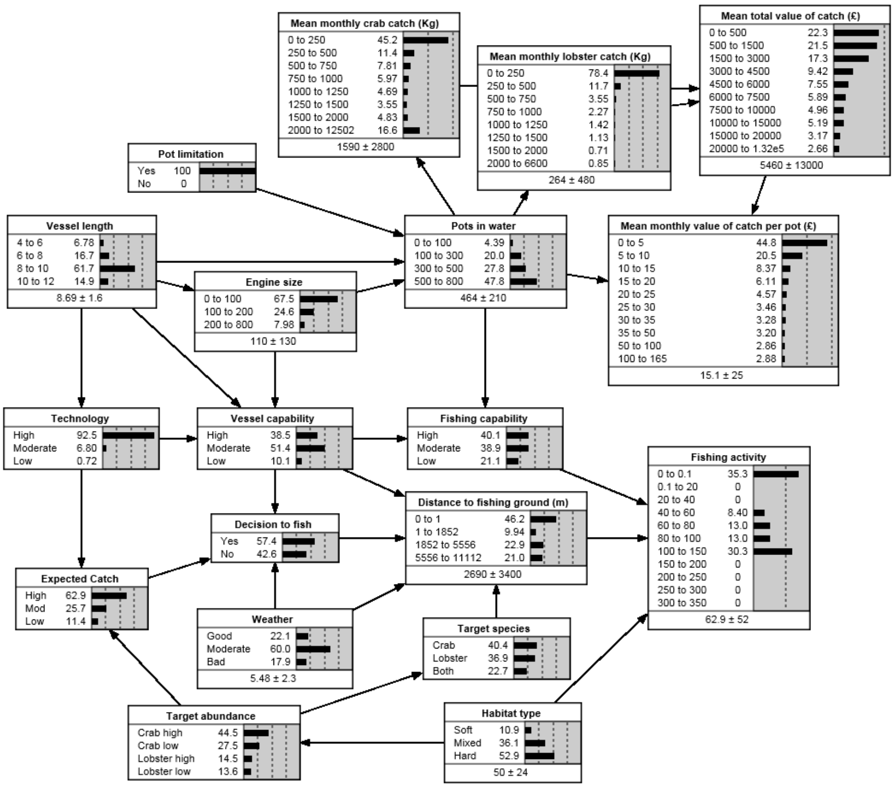


Fig 11. BBN model showing variables that affect fishing activity in Northumberland in winter at T2. Medians and standard deviations are shown for continuous data.

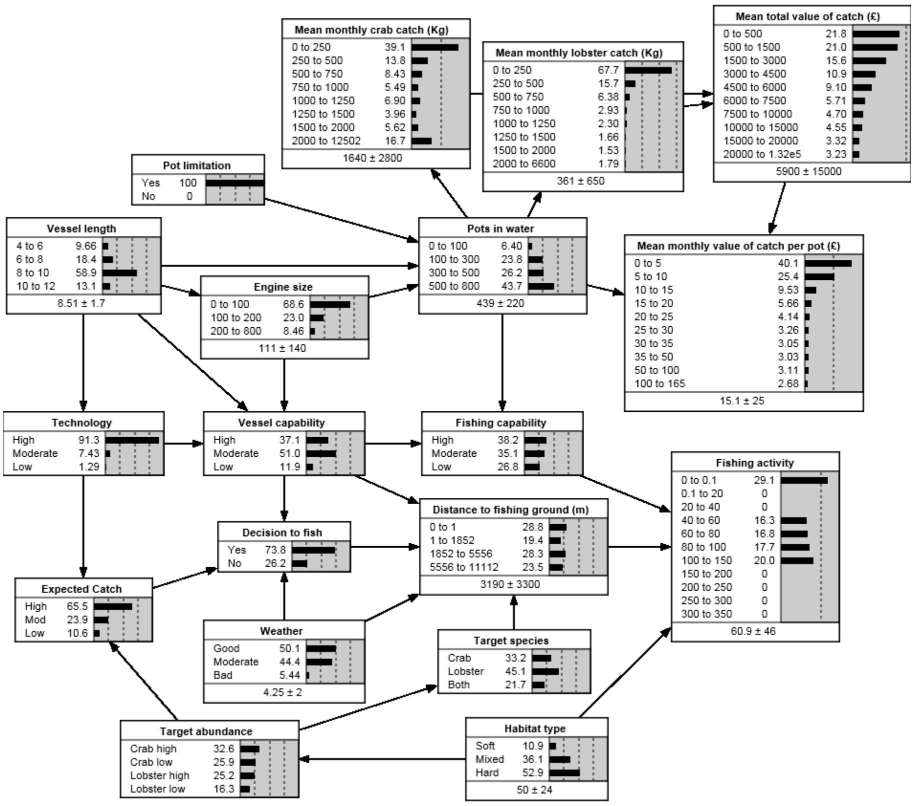


Fig 12. BBN model showing variables that affect fishing activity in Northumberland in spring at T2. Medians and standard deviations are shown for continuous data.

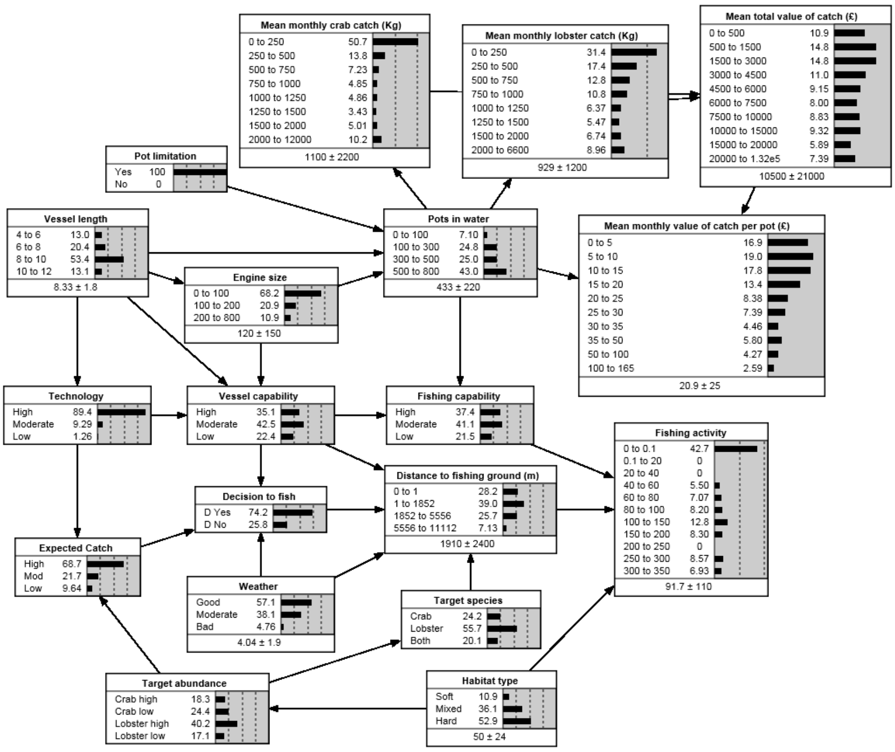


Fig 13. BBN model showing variables that affect fishing activity in Northumberland in summer at T2. Medians and standard deviations are shown for continuous data.

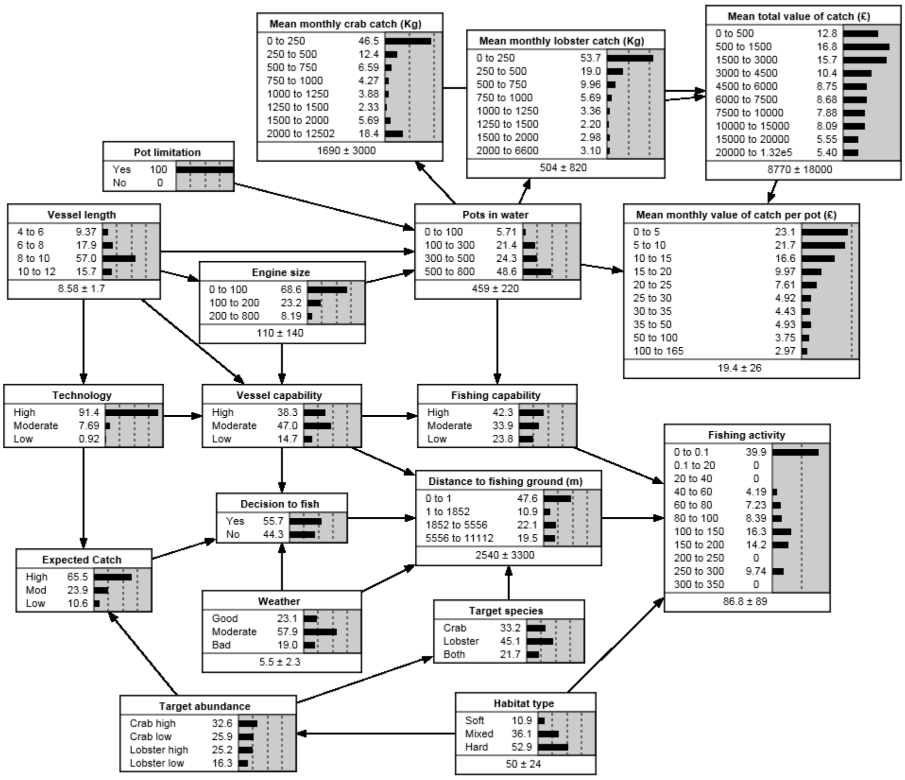


Fig 14. BBN model showing variables that affect fishing activity in Northumberland in autumn at T2. Medians and standard deviations are shown for continuous data.

6.3. Semi-structured questionnaire used for expert elicitation

Social, economic and environmental factors affecting fishing activity in the Northumberland

This questionnaire will inform three projects at Newcastle University (School of Marine Science and Technology) in partnership with Natural England and NIFCA. The aim of these studies are to investigate how social, economic and environmental factors interact and affect fishing activity in the Northumberland crab and lobster fishery.

The questionnaire will take approximately 60 mins and will cover aspects of your daily work potting in Northumberland.

The information from the project will be provided to Newcastle University, Natural England and NIFCA and will be treated as confidential and securely stored. Following standard NIFCA confidentiality practices:

- There will be no usage or publication of data by the project authors for identification of individual people or their vessels;
- The data are not processed to support measures or decisions with the respect to particular individuals;
- The data are not processed in such a way as that damage or distress is, or is likely to be, caused to any individual;

If you would like to be provided with further information regarding this project, or have any questions, please contact: Fabrice Stephenson (f.stephenson@ncl.ac.uk), Alex Aitken (A.Aitken1@ncl.ac.uk) or Li Wang (L.Wang47@newcastle.ac.uk).

I, ____, have read and understood the project information detailed above, been given the opportunity to ask questions and voluntarily agreed to participate in the questionnaire.

Signed: __________________________

Date: __________________________

General

Name: ____________________ Date: ____________ Time: ______________

Home port: ______________________

Vessel length: ________________________ Engine size: ________________

Number of years potting in the NIFCA district: __________________________

All questions in this survey refer to fishers targeting crab and lobster using baited - pots in the NIFCA district.

Vessel capability.

Q1. What proportion of the fleet fishing in the NIFCA district do you think has GPS equipped? And echosounder?

Q2. Has this stayed the same, increased or decreased over the last 15 years?

Q3. How has engine size on potting vessels in the NIFCA district changed over the last 15 years? (Prompt: stayed the same, increased, decreased)

Q4. What would you consider a small, moderate and large engine size for potting vessels operating in the NIFCA district? (Range: 4 – 750 engine horse power)

Small:___________ Moderate:____________ Large:______________

Q5. How has potting vessel length in Northumberland changed over the last 15 years? (Prompt: stayed the same, increased, decreased)

The next set of questions focusses on vessel capability: this is a combination of vessel length, engine size and equipment. For example, skippers of large boats with powerful engines may have different behaviours to skippers with small boats with small engines.

Q6. In terms of how capable a fishing vessel is, can you rank the importance of:

Vessel length:_________ Engine size:_________ Navigation equipment: _________

Q7. Have any changes in vessel capability over the last 15 years (i.e. vessel length, engine size, navigation equipment) allowed fishers to fish a greater number of pots?

Q8. Has the pot limitation in the NIFCA district affected the number of pots you fish? Do you think potting effort would be different without the pot limitation?

Q9. How do you think vessel capability (i.e. vessel length, engine size, navigation equipment) affects how far from the shore vessels are able or willing to pot?

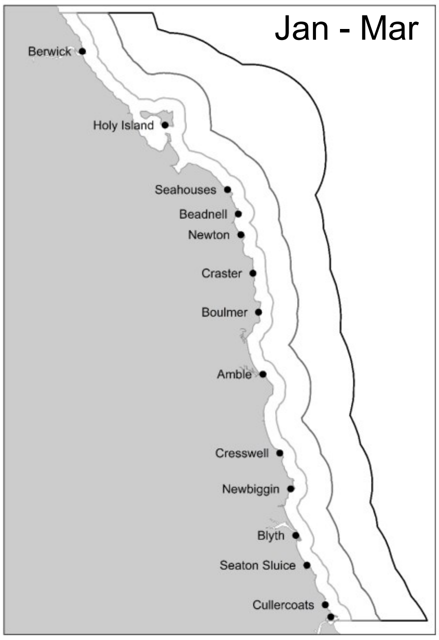
Weather and seasonal influence on decision making

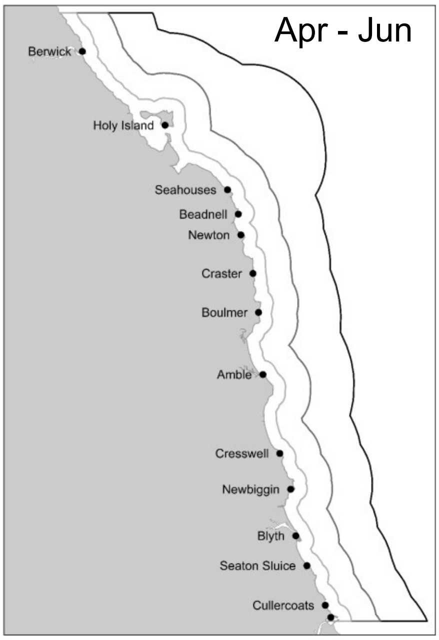
Q10. How does bad weather affect your fishing activity? (Prompt: Does bad weather limit the number of days potting vessels can leave port? What sea state and strength of wind (gale force) affects this?

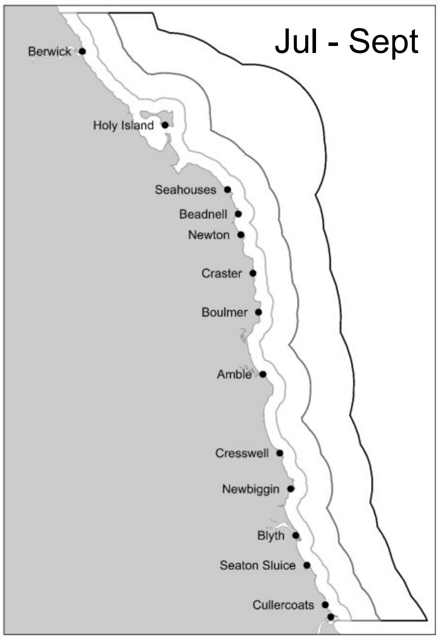
Q11. How does weather affect the distance from shore that fishers' pot? Does vessel length or engine size change this? (further investigation: damage to pots, danger to vessel, uncomfortable for fishermen)

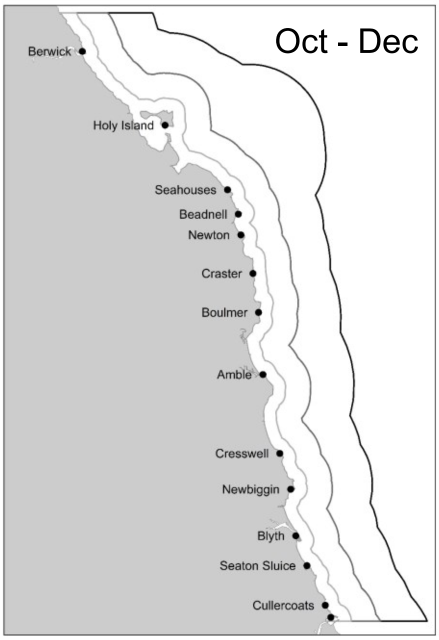
Q12. What determines seasonal changes in potting location? (Prompt: Is it due to weather damaging fishing gear; Is it to follow stocks i.e. seasonal biological patterns; Or a combination of both)

Q13. Percentage time spent in each distance (1; 1-3; 3-6 nmi) to shore per season in your fishing area.









Perceptions of habitat

Q14. How do you think fishers determine habitat? (Prompt: Is it technology or historic knowledge / catch?)

Q15. In the NIFCA district, do fishers move pots to soft sediment to limit damage to their gear in bad weather?

Q16. On what ground type do you think the highest number of lobster are found? And crab?

Target catch

Q17. For each season, what proportion of crab do you target and what proportion of lobster do you target?

Q18. Do you target a particular habitat depending on the time of year?

Q19. Has sonar and GPS increased the likelihood of better catches? Has this allowed new-comers to the potting fleet to be as successful as those with long-term knowledge? Why?

Q20. Out of ten hauls on the same fleet how often to you move these to a new potting ground? Does this vary depending on season?

Q21. Do you think that the actual number of crab and lobster on potting grounds changes between seasons or do you think it's easier to catch them at certain times of year?

Cost of fishing

Q22. In your opinion, how does vessel capability affect cost of potting? (i.e. vessel length, engine size)

Q23. Do you think the cost of fishing in the district has stayed the same, increased or decreased over the last 15 years? Why?

Q24. How does fuel price affect choice of fishing ground distance from port?

Q25. Has fuel price been an important consideration for your fishing activity over the last 15 years?

Q26. Does the cost of a fishing vessel license influence the decision to operate / buy large vessels? Why?

Effort

Q27. How many times per month do you haul all of the pots you fish in the NIFCA district? Prompt: does this vary seasonally?

Q28. What is the average soak time of pots that you fish in the NIFCA district? (Prompt: does this vary seasonally?)

Q29. Has the number of potting trips you make each month increased, decreased or stayed the same over the past 15 years? Can you expand on that please.

Q30. Have you observed a change in the last 15 years in potting activity outside the NIFCA district?

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